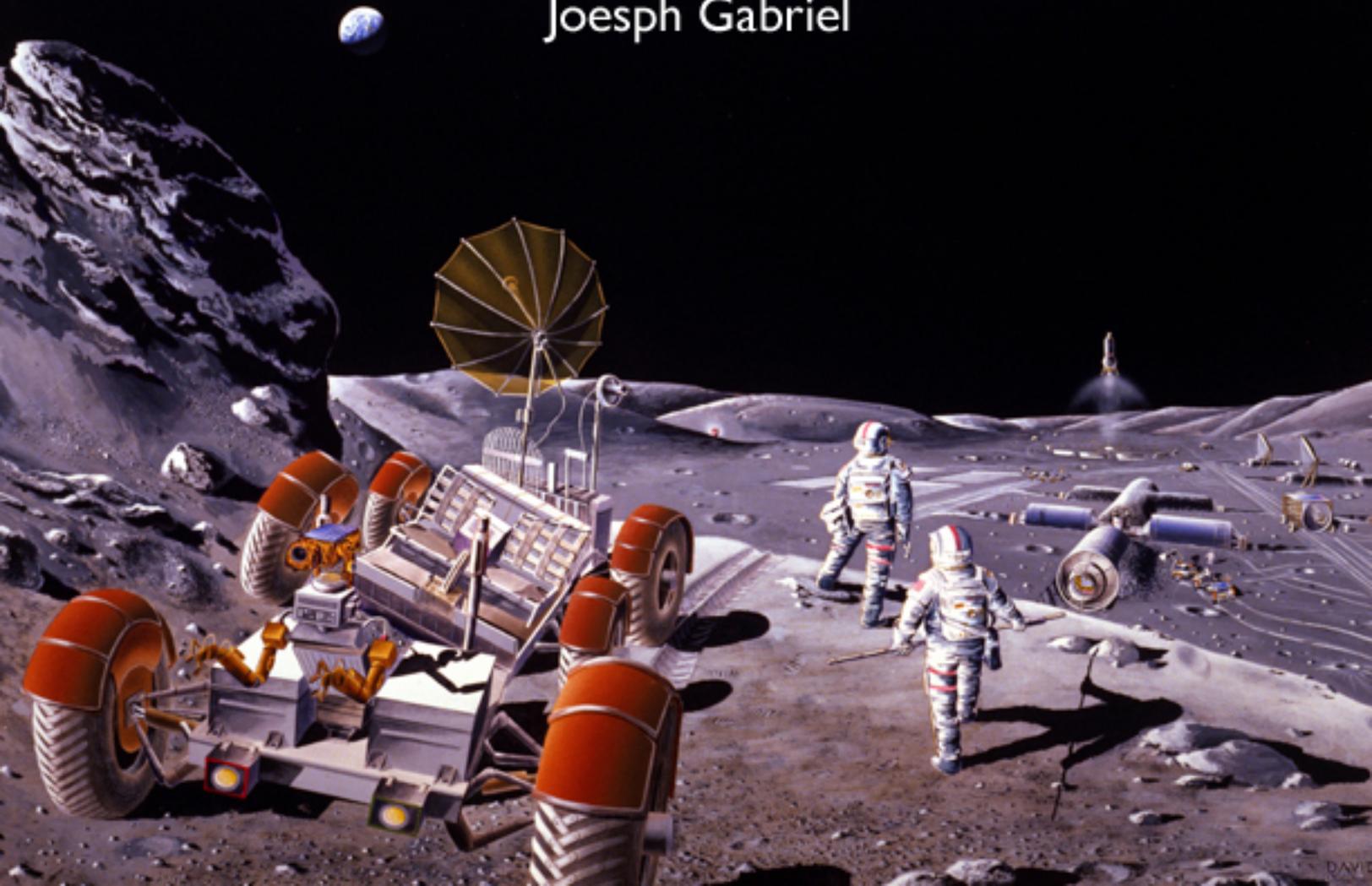


# Planetary Engineering & Space Colonization

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## Chapter-1

# Terraforming



An artist's conception shows a terraformed Mars in four stages of development.

**Terraforming** (literally, "Earth-forming") of a planet, moon, or other body is the hypothetical process of deliberately modifying its atmosphere, temperature, surface topography or ecology to be similar to those of Earth to make it habitable by terran organisms.

The term is sometimes used more generally as a synonym for planetary engineering, although some consider this more general usage an error. The concept of terraforming developed from both science fiction and actual science. The term was coined by Jack Williamson in a science-fiction story ("Collision Orbit") published during 1942 in *Astounding Science Fiction*, but the concept may pre-date this work.

Based on experiences with Earth, the environment of a planet can be altered deliberately; however the feasibility of creating an unconstrained planetary biosphere that mimics Earth on another planet has yet to be verified. Mars is considered by many to be the most likely candidate for terraforming. Much study has been done concerning the possibility of heating the planet and altering its atmosphere, and NASA has even hosted debates on the subject. Several potential methods of altering the climate of Mars may fall within humanity's technological capabilities, but at present the economic resources required to do so are far beyond that which any government or society is willing to allocate to the purpose. The long timescales and practicality of terraforming are the subject of debate. Other unanswered questions relate to the ethics, logistics, economics, politics, and methodology of altering the environment of an extraterrestrial world.

### ***History of scholarly study***

Carl Sagan, an astronomer, proposed the planetary engineering of Venus in an article published in the journal *Science* in 1961. Sagan imagined seeding the atmosphere of Venus with algae, which would convert water, nitrogen and carbon dioxide into organic compounds. As this process removed carbon dioxide from the atmosphere, the greenhouse effect would be reduced until surface temperatures dropped to "comfortable" levels. The resulting carbon, Sagan supposed, would be incinerated by the high surface temperatures of Venus, and thus be sequestered in the form of "graphite or some involatile form of carbon" on the planet's surface. However, later discoveries about the conditions on Venus made this particular approach impossible. One problem is that the clouds of Venus are composed of a highly concentrated sulfuric acid solution. Even if atmospheric algae could thrive in the hostile environment of Venus' upper atmosphere, an even more insurmountable problem is that its atmosphere is simply far too thick—the high atmospheric pressure would result in an "atmosphere of nearly pure molecular oxygen" and cause the planet's surface to be thickly covered in fine graphite powder. This volatile combination could not be sustained through time. Any carbon that was fixed in organic form would be liberated as carbon dioxide again through combustion, "short-circuiting" the terraforming process.

Sagan also visualized making Mars habitable for human life in "Planetary Engineering on Mars" (1973), an article published in the journal *Icarus*. Three years later, NASA addressed the issue of planetary engineering officially in a study, but used the term

"planetary ecosynthesis" instead. The study concluded that it was possible for Mars to support life and be made into a habitable planet. The first conference session on terraforming, then referred to as "Planetary Modeling", was organized that same year.

In March 1979, NASA engineer and author James Oberg organized the First Terraforming Colloquium, a special session at the Lunar and Planetary Science Conference in Houston. Oberg popularized the terraforming concepts discussed at the colloquium to the general public in his book *New Earths* (1981). Not until 1982 was the word *terraforming* used in the title of a published journal article. Planetologist Christopher McKay wrote "Terraforming Mars", a paper for the *Journal of the British Interplanetary Society*. The paper discussed the prospects of a self-regulating Martian biosphere, and McKay's use of the word has since become the preferred term. In 1984, James Lovelock and Michael Allaby published *The Greening of Mars*. Lovelock's book was one of the first to describe a novel method of warming Mars, where chlorofluorocarbons (CFCs) are added to the atmosphere. Motivated by Lovelock's book, biophysicist Robert Haynes worked behind the scenes to promote terraforming, and contributed the word *ecopoiesis* to its lexicon.

Beginning in 1985, Martyn J. Fogg began publishing several articles on terraforming. He also served as editor for a full issue on terraforming for the *Journal of the British Interplanetary Society* in 1991. In his book *Terraforming: Engineering Planetary Environments* (1995), Fogg proposed the following definitions for different aspects related to terraforming:

- Planetary engineering: the application of technology for the purpose of influencing the global properties of a planet.
- Geoengineering: planetary engineering applied specifically to the Earth. It includes only those macroengineering concepts that deal with the alteration of some global parameter, such as the greenhouse effect, atmospheric composition, insolation or impact flux.
- Terraforming: a process of planetary engineering, specifically directed at enhancing the capacity of an extraterrestrial planetary environment to support life as we know it. The ultimate achievement in terraforming would be to create an open planetary biosphere emulating all the functions of the biosphere of the Earth, one that would be fully habitable for human beings.
- Astrophysical engineering: taken to represent proposed activities, relating to future habitation, that are envisaged to occur on a scale greater than that of "conventional" planetary engineering.

Fogg also devised definitions for candidate planets of varying degrees of human compatibility:

- Habitable Planet (HP): A world with an environment sufficiently similar to the Earth as to allow comfortable and free human habitation.
- Biocompatible Planet (BP): A planet possessing the necessary physical parameters for life to flourish on its surface. If initially lifeless, then such a world

- could host a biosphere of considerable complexity without the need for terraforming.
- Easily Terraformable Planet (ETP): A planet that might be rendered biocompatible, or possibly habitable, and maintained so by modest planetary engineering techniques and with the limited resources of a starship or robot precursor mission.

Fogg suggests that Mars was a biologically compatible planet in its youth, but is not now in any of these three categories, since it could only be terraformed with greater difficulty. Mars Society founder Robert Zubrin produced a plan for a Mars return mission called Mars Direct that would set up a permanent human presence on Mars and steer efforts towards eventual terraformation.

### ***Requirements for sustaining terrestrial life***

An absolute requirement for life is an energy source, but the notion of planetary habitability implies that many other geophysical, geochemical, and astrophysical criteria must be met before the surface of an astronomical body is able to support life. Of particular interest is the set of factors that has sustained complex, multicellular animals in addition to simpler organisms on this planet. Research and theory in this regard is a component of planetary science and the emerging discipline of astrobiology.

In its astrobiology roadmap, NASA has defined the principal habitability criteria as "extended regions of liquid water, conditions favorable for the assembly of complex organic molecules, and energy sources to sustain metabolism."

### ***Preliminary stages of terraforming***

Once conditions become more suitable for life, the importation of microbial life could begin. As conditions approach that of Earth, plant life could also be brought in. This would accelerate the production of oxygen, which theoretically would make the planet eventually able to support animal and human life.

## *Prospective planets*



Artist's conception of a terraformed Mars

### **Mars**

In many respects, Mars is the most earthlike of all the other planets in our Solar system. Indeed, it is thought that Mars once did have a more Earth-like environment early in its history, with a thicker atmosphere and abundant water that was lost over the course of hundreds of millions of years.

The exact mechanism of this loss is still unclear, though three mechanisms in particular seem likely: First, whenever surface water is present, carbon dioxide reacts with rocks to form carbonates, thus drawing atmosphere off and binding it to the planetary surface. On Earth, this process is counteracted when plate tectonics works to cause volcanic eruptions

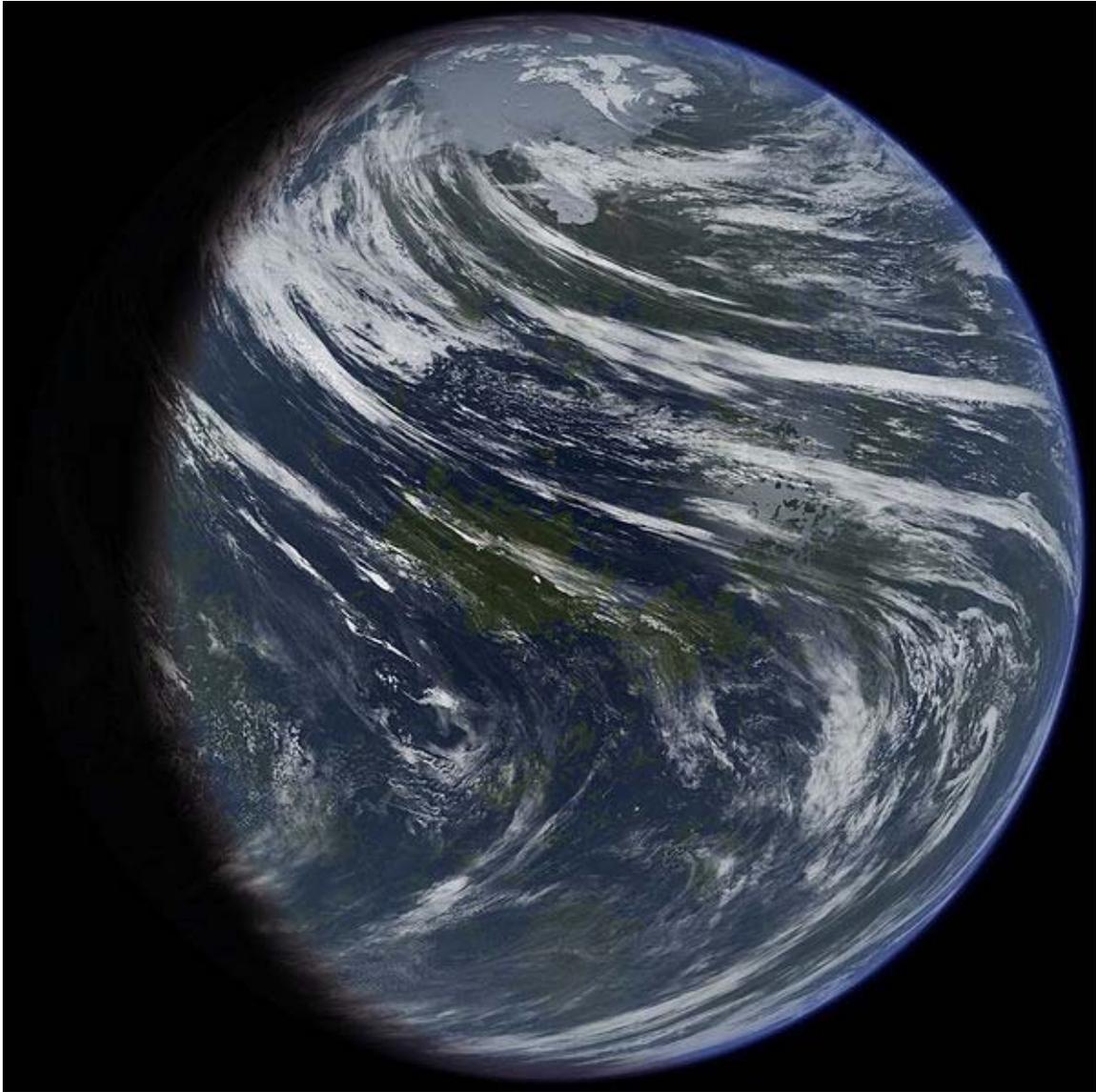
that vent carbon dioxide back to the atmosphere. On Mars, the lack of such tectonic activity worked to prevent the recycling of gases locked up in sediments.

Second, the lack of a magnetosphere surrounding the entire surface of Mars may have allowed the solar wind to gradually erode the atmosphere. Convection within the core of Mars, which is made mostly of iron, originally generated a magnetic field. However the dynamo ceased to function long ago, and the magnetic field of Mars has largely disappeared, probably due to "... loss of core heat, solidification of most of the core, and/or changes in the mantle convection regime." Mars does still retain a limited magnetosphere that covers approximately 40% of its surface. Rather than uniformly covering and protecting the atmosphere from solar wind, however, the magnetic field takes the form of a collection of smaller, umbrella-shaped fields, mainly clustered together around the planet's southern hemisphere. It is within these regions that chunks of atmosphere are violently "blown away", as astronomer David Brain explains:

The joined fields wrapped themselves around a packet of gas at the top of the Martian atmosphere, forming a magnetic capsule a thousand kilometres wide with ionised air trapped inside... Solar wind pressure caused the capsule to 'pinch off' and it blew away, taking its cargo of air with it.

Finally, between approximately 4.1 and 3.8 billion years ago, asteroid impacts during the Late Heavy Bombardment caused significant changes to the surface environment of objects in our Solar system. The low gravity of Mars suggests that these impacts could have ejected much of the Martian atmosphere into deep space.

Terraforming Mars would entail two major interlaced changes: building the atmosphere and heating it. A thicker atmosphere of greenhouse gases such as carbon dioxide would trap incoming solar radiation. Because the raised temperature would add greenhouse gases to the atmosphere, the two processes would augment each other.



Artist's conception of a terraformed Venus

## **Venus**

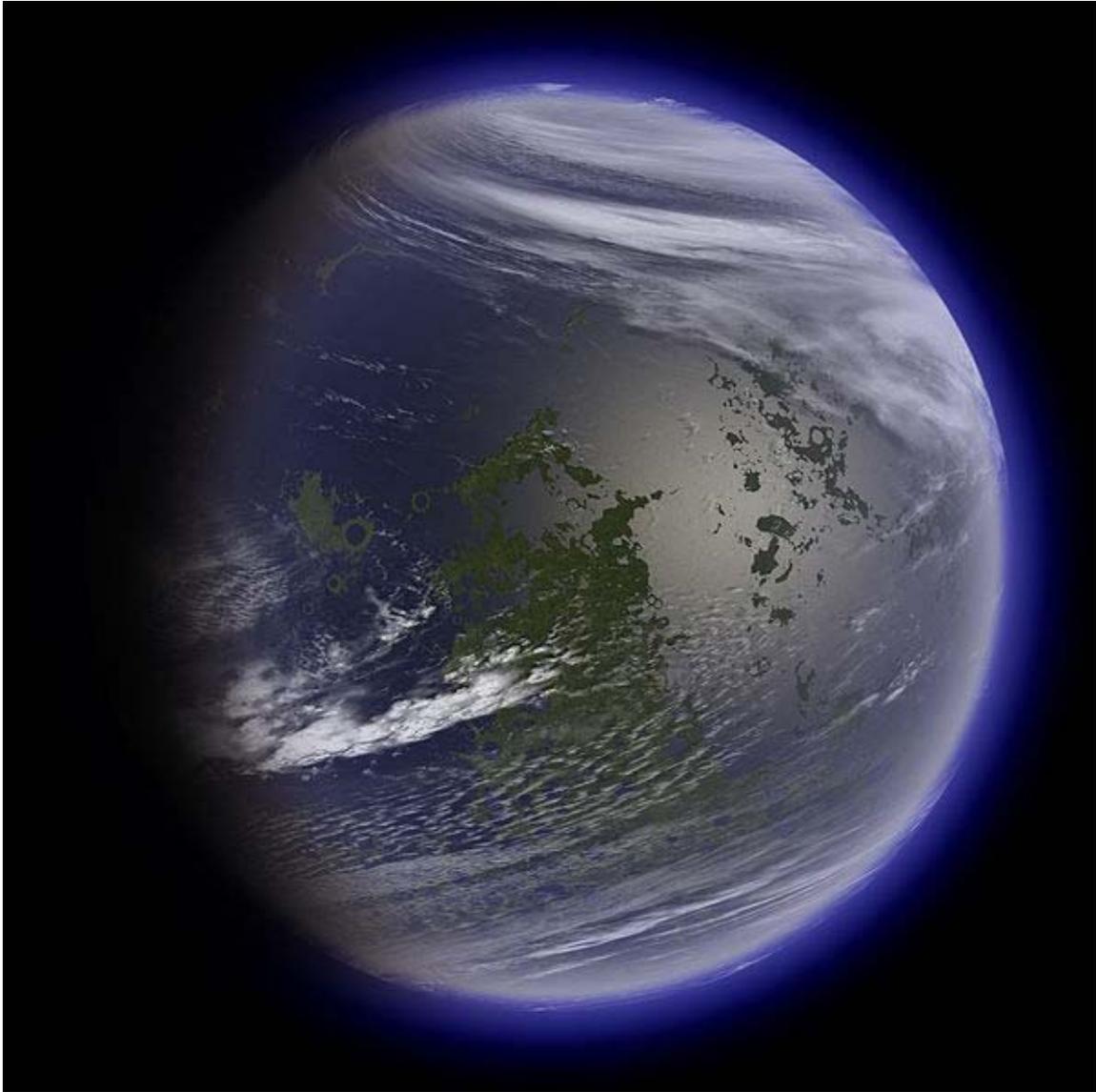
Terraforming Venus requires two major changes; removing most of the planet's dense 9 MPa carbon dioxide atmosphere and reducing the planet's 450 °C (723.15 K) surface temperature. These goals are closely interrelated, since Venus' extreme temperature is thought to be due to the greenhouse effect caused by its dense atmosphere. Sequestering the atmospheric carbon would likely solve the temperature problem as well.



Artist's conception of a terraformed Europa

### **Europa (moon)**

Europa, a moon of Jupiter, is a potential candidate for terraforming. One advantage to Europa is the presence of liquid water which could be extremely helpful for the introduction of any form of life. The difficulties are numerous; Europa is near a huge radiation belt around Jupiter. This would require the building of radiation deflectors, which is currently impractical. Additionally, this satellite is covered in ice and would have to be heated, and there would need to be a supply of oxygen, though this could, at sufficient energy cost, be manufactured locally by electrolysis of the copious water available.



Artist's conception of what the Moon might look like terraformed

### **Other planets and solar system entities**

Other possible candidates for terraforming (possibly only partial or paraterraforming) include Titan, Callisto, Ganymede, the Moon, and even Mercury, Saturn's moon Enceladus and the dwarf planet Ceres. Most, however, have too little mass and gravity to hold an atmosphere indefinitely (although it is possible, but not certain, that an atmosphere could remain for tens of thousands of years or be replenished as needed). In addition, aside from the Moon and Mercury, most of these worlds are so far from the Sun that adding sufficient heat would be much more difficult than even Mars would be. Terraforming Mercury would present a different series of challenges, but in certain aspects would be easier than terraforming Venus. Though not widely discussed, the possibility of terraforming Mercury's poles has been presented. Saturn's Titan offers

several unique advantages, such as an atmospheric pressure similar to Earth and an abundance of nitrogen and frozen water. Jupiter's moons Europa, Ganymede, and Callisto also have an abundance of water ice.

## ***Paraterraforming***

Also known as the "worldhouse" concept, or domes in smaller versions, paraterraforming involves the construction of a habitable enclosure on a planet which eventually grows to encompass most of the planet's usable area. The enclosure would consist of a transparent roof held one or more kilometers above the surface, pressurized with a breathable atmosphere, and anchored with tension towers and cables at regular intervals. Proponents claim worldhouses can be constructed with technology known since the 1960s. The Biosphere 2 project built a dome on Earth that contained a habitable environment. The project encountered difficulties in construction and operation.

Paraterraforming has several advantages over the traditional approach to terraforming. For example, it provides an immediate payback to investors (assuming a capitalistic financing model); the worldhouse starts out small in area (a domed city for example), but those areas provide habitable space from the start. The paraterraforming approach also allows for a modular approach that can be tailored to the needs of the planet's population, growing only as fast and only in those areas where it is required. Finally, paraterraforming greatly reduces the amount of atmosphere that one would need to add to planets like Mars to provide Earth-like atmospheric pressures. By using a solid envelope in this manner, even bodies which would otherwise be unable to retain an atmosphere at all (such as asteroids) could be given a habitable environment. The environment under an artificial worldhouse roof would also likely be more amenable to artificial manipulation.

It has the disadvantage of requiring massive amounts of construction and maintenance activity. It also would not likely have a completely independent water cycle, as rainfall may be able to develop with a high enough roof, but still probably not efficiently enough for agriculture or a water cycle. The extra cost might be off-set somewhat by automated manufacturing and repair mechanisms. A worldhouse might also be more susceptible to catastrophic failure if a major breach occurred, though this risk might be reduced by compartmentalization and other active safety precautions. Meteor strikes are a particular concern because without any external atmosphere they would reach the surface before burning up.

## ***Ethical issues***

There is a philosophical debate within biology and ecology as to whether terraforming other worlds is an ethical endeavor. From the point of view of a cosmocentric ethic, this involves balancing the need for the preservation of human life against the intrinsic value of existing planetary ecologies. On the pro-terraforming side of the argument, there are those like Robert Zubrin, Martyn J. Fogg, Richard L. S. Taylor and the late Carl Sagan who believe that it is humanity's moral obligation to make other worlds suitable for life, as a continuation of the history of life transforming the environments around it on Earth.

They also point out that Earth would eventually be destroyed if nature takes its course, so that humanity faces a very long-term choice between terraforming other worlds or allowing all terrestrial life to become extinct. Terraforming totally barren planets, it is asserted, is not morally wrong as it does not affect any other life.

Others believe terraforming would be an unethical interference in nature, and that given humanity's past treatment of the Earth, other planets may be better off without human interference. Still others strike a middle ground, such as Christopher McKay, who argues that terraforming is ethically sound only once we have completely assured that an alien planet does not harbor life of its own; but that if it does, while we should not try to reshape the planet to our own use, we should engineer the planet's environment to artificially nurture the alien life and help it thrive and co-evolve, or even co-exist with humans. Even this would be seen as a type of terraforming to the strictest of ecocentrists, who would say that all life has the right, in its home biosphere, to evolve at its own pace as well as its own direction, free of any outside interference, apparently even when it lacks volition of its own, for evolution is not a personally directed process in non-sapient species.

### ***Economic issues***

The initial cost of such projects as planetary terraforming would be gargantuan, and the infrastructure of such an enterprise would have to be built from scratch. Such technology is not yet developed, let alone financially feasible at the moment. John Hickman has pointed out that almost none of the current schemes for terraforming incorporate economic strategies, and most of their models and expectations seem highly optimistic. Access to the vast resources of space may make such projects more economically feasible, though the initial investment required to enable easy access to space will likely be tremendous.

### ***Political issues***

There are potential political issues arising from terraforming a planet. National pride, rivalries between nations, and the politics of public relations have been a primary motivation for shaping space projects.

## Chapter-2

# Geoengineering



An oceanic phytoplankton bloom in the South Atlantic Ocean, off the coast of Argentina. Encouraging such blooms with iron fertilization could lock up carbon on the seabed.

The modern concept of **geoengineering** (or **climate engineering**) typically proposals to deliberately manipulate the Earth's climate to counteract the effects of global warming

from greenhouse gas emissions. Other uses of the word sometimes occur, meaning geotechnical engineering.

The National Academy of Sciences defined geoengineering as "options that would involve large-scale engineering of our environment in order to combat or counteract the effects of changes in atmospheric chemistry." IPCC (2007) concluded that geoengineering options, such as ocean fertilization to remove CO<sub>2</sub> from the atmosphere, remained largely unproven. It was judged that reliable cost estimates for geoengineering had not yet been published.

Geoengineering accompanies mitigation and adaptation to form a 3-stranded 'MAG' approach to tackling global warming, notably advocated by the Institution of Mechanical Engineers. Some geoengineering techniques are based on carbon sequestration. These techniques seek to reduce greenhouse gases in the atmosphere directly. These include direct methods (e.g. carbon dioxide air capture) and indirect methods (e.g. ocean iron fertilization). These techniques can be regarded as mitigation of global warming. Alternatively, solar radiation management techniques do not reduce greenhouse gas concentrations, and can only address the warming effects of carbon dioxide and other gases; they cannot address problems such as ocean acidification, which are expected as a result of rising carbon dioxide levels. Examples of proposed solar radiation management techniques include the production of stratospheric sulfur aerosols, which was suggested by Paul Crutzen, space mirrors, and cloud reflectivity enhancement. Most techniques have at least some side effects.

To date, no large-scale geoengineering projects have been undertaken. Some limited tree planting and cool roof projects are already underway, and ocean iron fertilization is at an advanced stage of research, with small-scale research trials and global modelling having been completed. Field research into sulfur aerosols has also started. Some commentators have suggested that consideration of geoengineering presents a moral hazard because it threatens to reduce the political and popular pressure for emissions reduction. Typically, the scientists and engineers proposing geoengineering strategies do not suggest that they are an alternative to emissions control, but rather an accompanying strategy. Reviews of geoengineering techniques have emphasised that they are not substitutes for emission controls and have identified potentially stronger and weaker schemes.

## **Definition**

Geoengineering is the idea of applying planetary engineering to Earth. Geoengineering would involve the deliberate modification of Earth's environment on a large scale "to suit human needs and promote habitability". Typically, the term is used to describe proposals to counter the effects of human-induced climate change. However, others define it more narrowly as nature-integrated engineering projects. The term *geoengineering* is distinct from environmental damage and accidental anthropogenic climate change, which are side-effects of human activity, rather than an intended consequence. The global recovery of hydrocarbons from the subsurface using integrated geoscience and engineering

technology has been termed 'petroleum geoengineering' as an activity with global impact. Definitions of the term are not universally accepted.

## ***Background***

The field is currently experiencing a surge of interest as it has now become broadly accepted that global warming is both real and dangerous. A degree of urgency in efforts to research and implement potential solutions is based on the historic failure to control emissions, and the possibility that tipping points in the Earth's climate system are close at hand. In particular the Arctic shrinkage is causing accelerated regional warming. Rapid action with geoengineering may be necessary. Other tipping points might be avoided by reducing the impact of global warming in order to stifle positive feedback and prevent the resulting accelerated climate change.

The study of geoengineering is a complex discipline, as it requires the collation of knowledge in:

- scientific disciplines including atmospheric chemistry, ecology, meteorology, plant biology
- engineering disciplines including aeronautical engineering, naval architecture, ballistics
- management and control disciplines such as risk management, operational research, cost-benefit analysis

Several notable organisations have recently, or are soon to, investigate geoengineering with a view to evaluating its potential. Notably, NASA, the Royal Society, the Institute of Mechanical Engineers, and the UK Parliament, have all held inquiries or contests aimed at discovering and evaluating current knowledge of the subject. The Asilomar International Conference on Climate Intervention Technologies was convened to identify and develop risk reduction guidelines for climate intervention experimentation.

The major environmental organisations such as Friends of the Earth and Greenpeace have typically been reluctant to endorse geoengineering. Some have argued that any public support for geoengineering may weaken the fragile political consensus to reduce greenhouse gas emissions.

## ***Proposed strategies***

Several geoengineering strategies have been proposed. The documentaries *Five ways to save the world* and *La temperature grimpe* describe many of the most notable projects. IPCC documents also detail several proposed projects.

### **Solar radiation management**

Solar radiation management (SRM) projects seek to reduce the amount of sunlight hitting the Earth and thus counteract global warming. They do not reduce greenhouse gas

concentrations in the atmosphere, and thus do not address problems such as ocean acidification caused by these gases. The phenomenon of global dimming as a side-effect of fossil fuel use is widely known, and is not necessarily a geoengineering technique, also occurring naturally as a result of volcanoes and major forest fires. However, its deliberate manipulation is a tool of the geoengineer.

Solar radiation management projects often have the advantage of speed. While greenhouse gas remediation offers a comprehensive possible solution to climate change, it does not give instant results; for that, solar radiation management is required.

Techniques that fall into this category include:

- Creating stratospheric sulfur aerosols
- Ocean foams
- Cool roof—using pale-coloured roofing and paving materials
- Cloud reflectivity enhancement – using fine sea water spray to whiten clouds and increase cloud reflectivity.
- Space sunshade—obstructing solar radiation with space-based mirrors or other structures
- Cloud seeding of cirrus clouds, possibly using airliners.

## **Greenhouse gas remediation**

Greenhouse gas remediation projects seek to remove greenhouse gases from the atmosphere, and thus tackle the root cause of global warming. They either directly remove greenhouse gases, or alternatively seek to influence natural processes to remove greenhouse gases indirectly. These projects offer a comprehensive solution to the problem of excess greenhouse gases in the atmosphere, but they will take many years to work fully. Many projects overlap with carbon capture and storage and carbon sequestration projects, and may not be considered to be geoengineering by all commentators. Techniques in this category include:

- Ocean nourishment including Iron fertilisation of the oceans
- Creating biochar (anaerobic charcoal) and burying it to create terra preta
- Bio-energy with carbon capture and storage
- Carbon air capture to remove carbon dioxide from ambient air

## **Arctic geoengineering**

Various hydrological geoengineering projects aim to change the climate without directly or indirectly removing greenhouse gases, or directly influencing solar radiation. These principally act by limiting Arctic sea ice loss. Keeping the Arctic ice is seen by many commentators as vital, due to its role in the planet's albedo and in keeping methane, which is an important greenhouse gas, locked up in permafrost.

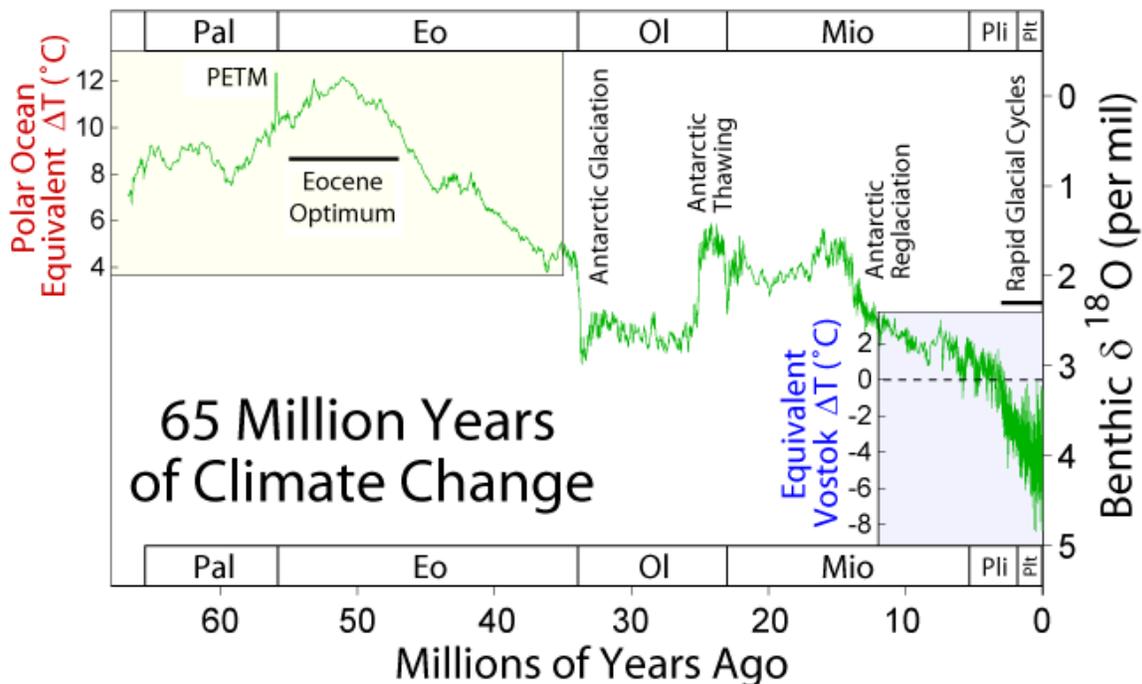
## Heat transport

The use of vertical ocean pipes to mix cooler deep water and warmer surface water has been proposed. This technology has also been suggested for the disruption of hurricanes by Bill Gates and others in a recent patent application. Modification of hurricanes may be considered weather modification rather than geoengineering, depending on the definition used.

## Justification

The use of geoengineering to tackle climate change is advocated for several specific reasons:

## Tipping points and positive feedback



Climate change during the last 65 million years. The Paleocene–Eocene Thermal Maximum is labelled PETM.

It is argued that climate change has already, or is soon to have passed one or more tipping points where aspects of the climate system may 'tip' from one stable state to another stable state, much like a glass tipping over. When the new stable state is reached, it may trigger or accelerate warming positive feedback effects, such as the collapse of Arctic sea ice triggering the release of methane from permafrost in Siberia. The "nightmare scenario" is that a domino effect will occur, with successive parts of the climate system tipping one after the other, with each change being caused by the previous one and causing the next one. Such a situation will lead to spiralling and potentially sudden climate change.

The precise identity of such "tipping points" is not clear, with scientists taking differing views on whether specific systems are capable of "tipping" and the point at which this "tipping" will occur. An example of a previous tipping point is that which preceded the rapid warming leading up to the Paleocene–Eocene Thermal Maximum. Once the tipping point is reached, cuts in greenhouse gas emissions will not be able to reverse the change. Depending on the precise nature of the individual system that "tips", positive feedbacks may occur, with warming causing more warming, which causes yet more warming—a runaway global warming event. Therefore, some commentators suggest that more conservative use of resources is not enough to mitigate global warming. Even if all greenhouse emissions suddenly came to a complete halt, the world would continue to be affected for centuries, and further warming may occur due to positive feedback. Conservation of resources and reduction of greenhouse emissions, used in conjunction with geoengineering, are therefore considered a viable option. Geoengineering offers the hope of temporarily reversing some aspects of climate change and allowing the natural climate to be substantially preserved whilst greenhouse gas emissions are brought under control and removed from the atmosphere by natural or artificial processes.

### **Precautionary principle**

Bearing in mind the threats from climate change, it can be argued that attempting geoengineering represents a lesser risk than not pursuing such strategies. While the understanding of geoengineering techniques is limited, the risks of global warming are at least partially understood, and are severe.

### **Costs**

Some geoengineering techniques, such as the use of pale-coloured materials for roofing and paving, can be achieved at little or no cost, and may even offer a financial payback. IPCC (2007) concluded that reliable cost estimates for geoengineering options had not been published. This finding was based on medium agreement in the literature and limited evidence.

### **Political viability**

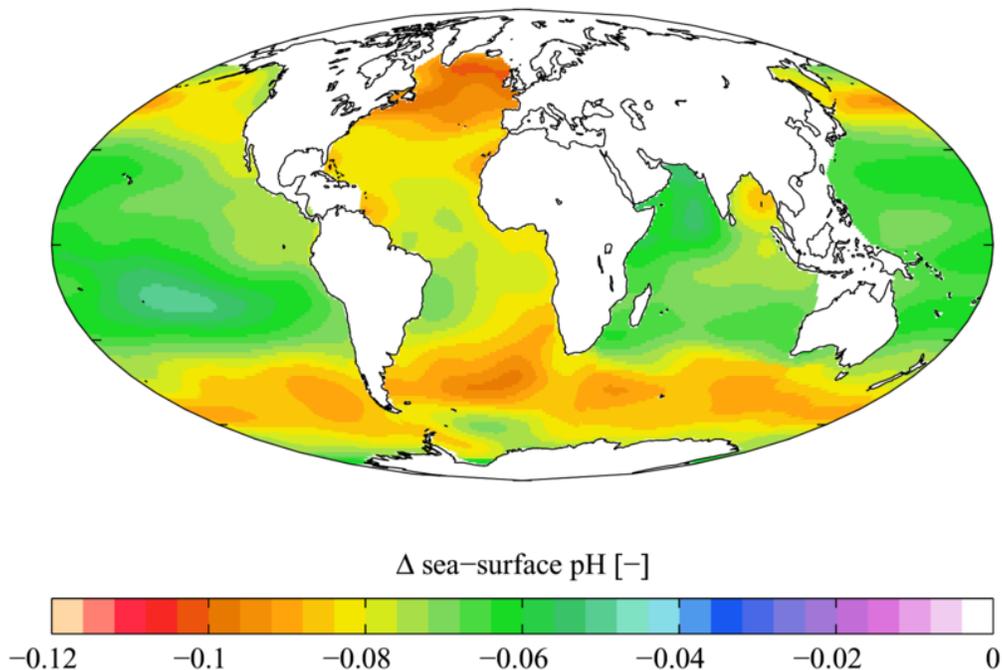
It has been argued that regardless of the economic, scientific and technical aspects, the difficulty of achieving concerted political action on climate change requires other approaches. Those arguing political expediency say the difficulty of achieving meaningful emissions cuts and the effective failure of the Kyoto Protocol demonstrate the practical difficulties of achieving carbon dioxide emissions reduction by the agreement of the international community. However, others point to support for geoengineering proposals among think tanks with a history of climate change skepticism and opposition to emissions reductions as evidence that the prospect of geoengineering is itself already politicized and being promoted as part of an argument against the need for (and viability of) emissions reductions; that, rather than geoengineering being a solution to the difficulties of emissions reductions, the prospect of geoengineering is being used as part of an argument to stall emissions reductions in the first place.

## ***Risks and criticisms***

Various criticisms have been made of geoengineering. However, the existence of criticism should not be taken to mean that those raising it are opposed to a particular technique, but rather that they are pointing out a potential disadvantage or downside which may need to be monitored or controlled, or may alternatively weigh against a particular technique. Some commentators appear fundamentally opposed, however. Individuals such as Raymond Pierrehumbert have called for a moratorium on geoengineering techniques.

## **Ineffectiveness**

The effectiveness of the schemes proposed may fall short of predictions. In ocean iron fertilization, for example, the amount of carbon dioxide removed from the atmosphere may be much lower than predicted, as carbon taken up by plankton may be released back into the atmosphere from dead plankton, rather than being carried to the bottom of the sea and sequestered.



Change in sea surface pH caused by anthropogenic CO<sub>2</sub> between the 1700s and the 1990s. This ocean acidification will still be a major problem unless atmospheric CO<sub>2</sub> is reduced.

## **Incomplete solution to CO<sub>2</sub> emissions**

Techniques that do not remove greenhouse gases from the atmosphere may control global warming, but do not reduce other effects from these gases, such as ocean acidification.

While not an argument against geoengineering *per se*, this is an argument against reliance on geoengineering to the exclusion of greenhouse gas reduction.

## **Control and predictability problems**

The full effects of various geoengineering schemes are not well understood. Matthews et al. compared geoengineering to a number of previous environmental interventions and concluded that "Given our current level of understanding of the climate system, it is likely that the result of at least some geoengineering efforts would follow previous ecological examples where increased human intervention has led to an overall increase in negative environmental consequences."

Performance of the systems may become ineffective, unpredictable or unstable as a result of external events, such as volcanic eruptions, phytoplankton blooms, El Niño, solar flares, etc., potentially leading to profound and unpredictable disruption to the climate system.

It may be difficult to predict the effectiveness of projects, with models of techniques giving widely varying results. In the instances of systems which involve tipping points, this may result in irreversible effects. Climate modelling is far from an exact science even when applied to comparatively well-understood natural climate systems, and it is made more complex by the need to understand novel and unnatural processes which by definition lack relevant observation data.

## **Side effects**

The techniques themselves may cause significant foreseen or unforeseen harm. For example, the use of reflective balloons may result in significant litter, which may be harmful to wildlife.

Ozone depletion is a risk of some geoengineering techniques, notably those involving sulfur delivery into the stratosphere.

The active nature of geoengineering may in some cases create a clear division between winners and losers. Most of the proposed interventions are regional, such as albedo modification in the Arctic. Necessarily, such interventions compel those in the affected regions to tolerate the effects of geoengineering for the supposed benefit of the global climate.

There may be unintended climatic consequences, such as changes to the hydrological cycle including droughts or floods, caused by the geoengineering techniques, but possibly not predicted by the models used to plan them. Such effects may be cumulative or chaotic in nature, making prediction and control very difficult.

## **Unreliable systems**

The performance of the interventions may be inconsistent due to mechanical failure, non-availability of consumables or funding problems.

The geoengineering techniques would, in many instances, be vulnerable to being switched off or deliberately destroyed. As examples, cloud making ships could be switched off or sunk and space mirrors could be tilted to make them useless. Anyone capable of exerting such power may seek to abuse it for commercial gain, military advantage or simple terrorism.

## **Weaponisation**

The Environmental Modification Convention generally prohibits weaponising geoengineering techniques. However, this does not eliminate the risk. Geoengineering techniques may serve as weapons of mass destruction, creating droughts or famines designed to destroy or disable an enemy. They could also be used simply to make battlefield conditions more favourable to one side or the other in a war (such as in Operation Popeye). For example, laser-guided weapons are confounded by clouds, and thus switching off cloud machines would favour forces using such weapons, and switching them on would favour ground forces defending against them.

Whilst laws or treaties may prevent the manipulation of the climate as a weapon of war, it could be argued that geoengineering is itself a manipulation, and thus destroying or disabling the geoengineering structures is not prohibited. A new legal framework may be necessary in the event that large-scale geoengineering becomes established.

Carnegie's Ken Caldeira said, "It will make it harder to achieve broad consensus on developing and governing these technologies if there is suspicion that gaining military advantage is an underlying motivation for its development..."

## **Effect on sunlight, sky and clouds**

Managing solar radiation using aerosols or cloud cover will change the ratio between direct and indirect solar radiation. This may affect plant life and solar energy. There will be a significant effect on the appearance of the sky from aerosol projects, notably a hazing of blue skies and a change in the appearance of sunsets. Aerosols may affect the formation of clouds, especially cirrus clouds.

## **Moral hazard**

The existence of such techniques may reduce the political and social impetus to reduce carbon emissions.

Other criticism comes from those who see geoengineering projects as reacting to the symptoms of global warming rather than addressing the real causes of climate change.

Because geoengineering is a form of controlling the risks associated with global warming, it leads to a moral hazard problem. The problem is that knowledge that geoengineering is possible could lead to climate impacts seeming less fearsome, which could in turn lead to a weaker commitment to reducing greenhouse gas emissions.

### **Lack of global control**

Geoengineering opens up various political and economic issues. David Keith argues that the cost of geoengineering the Earth is within the realm of small countries, large corporations, or even very wealthy individuals. Steve Rayner agrees that not all geoengineering possibilities are expensive, and that some, such as ocean iron fertilisation, are within the reach of very wealthy individuals, calling them a "Greenfinger" (after the fictional Goldfinger). David Victor suggests that geoengineering is within the reach of any individual who has a small fraction of the bank account of Bill Gates, who takes it upon him or her self to be the "self-appointed protector of the planet".

This effectively eliminates any control over who gets to decide when to cool the Earth and how often this should be done. The resulting power would be enormous, and could not necessarily be readily controlled by legal, political or regulatory systems. These legal and regulatory systems may themselves be far less powerful than the geoengineers controlling the climate become.

It is quite feasible for carbon offsetting firms to set up unregulated, unsupervised and dangerous geoengineering projects. This may be done in order to sell carbon credits to individuals and firms.

Geoengineering schemes have the potential to cause significant environmental damage, and may even end up releasing further greenhouse gases into the atmosphere. Opposition to some early schemes has been intense, with respected environmental groups campaigning against them.

### **Rapid warming if stopped**

If solar radiation management were to abruptly stop, the climate would rapidly warm. This would cause a sudden rise in global temperatures towards levels which would have existed without the use of the geoengineering technique. The rapid rise in temperature may lead to more severe consequences than a gradual rise of the same magnitude.

### ***Implementation issues***

There is no general consensus that geoengineering is safe, appropriate or effective, for the reasons listed above. The issue of moral hazard means that many environmental groups and campaigners are reluctant to advocate geoengineering for fear of reducing the imperative to cut greenhouse gas emissions. Other environmentalists see calls for geoengineering as part of an explicit strategy to delay emissions reductions on the part of those with connections to coal and oil industries.

All proposed geoengineering techniques require implementation on a relatively large scale, in order to make a significant difference to the Earth's climate. The least costly schemes are budgeted at a cost of millions, with many more complex schemes such as space sunshade costing far more.

Many techniques, again such as space sunshade, require a complex technical development process before they are ready to be implemented. There is no clear institutional mechanism for handling this research and development process. As a result, many promising techniques do not have the engineering development or experimental evidence to determine their feasibility or efficacy at present.

Once a technique has been developed and tested, its implementation is still likely to be difficult. Climate change is by nature a global problem, and therefore no one institution, company or government is responsible for it. The substantial costs of most geoengineering techniques therefore cannot currently be apportioned. Roll-out of such technologies is therefore likely to be delayed until these issues can be resolved. A notable exception is the use of small albedo manipulation projects, known as *cool roof*, in which the colour of roofing or paving surfaces can be manipulated to reflect solar radiation back into space. These can be, and are, implemented by individuals, companies and governments without controversy.

Due to the radical changes caused by geoengineering interventions, legal issues are also an impediment to implementation. The changes resulting from geoengineering necessarily benefit some people and disadvantage others. There may therefore be legal challenges to the implementation of geoengineering techniques by those adversely affected by them.

## ***Evaluation of geoengineering***

Few field experiments in geoengineering have been carried out. Most of what is known about the suggested techniques is based on small-scale trials and from simulations of global climate models and other computer modelling techniques. Some geoengineering schemes employ methods that have analogues in natural phenomena such as stratospheric sulfur aerosols and cloud condensation nuclei. As such, studies about the efficacy of these schemes can draw on information already available from other research, such as that following the 1991 eruption of Mount Pinatubo. However, comparative evaluation of the relative merits of each technology is complicated, especially given modelling uncertainties and the early stage of engineering development of many geoengineering schemes.

In a 2009 review study, Lenton and Vaughan evaluated a range of geoengineering schemes from those that sequester CO<sub>2</sub> from the atmosphere and decrease longwave radiation trapping, to those that decrease the Earth's receipt of shortwave radiation. In order to permit a comparison of disparate techniques, they used a common evaluation for each scheme based on its effect on net radiative forcing. As such, the review examined the scientific plausibility of schemes rather than the practical considerations such as

engineering feasibility or economic cost. Lenton and Vaughan found that "[air] capture and storage shows the greatest potential, combined with afforestation, reforestation and bio-char production", and noted that "other suggestions that have received considerable media attention, in particular "ocean pipes" appear to be ineffective". They concluded that "[climate] geoengineering is best considered as a potential complement to the mitigation of CO<sub>2</sub> emissions, rather than as an alternative to it".

Reports into geoengineering have also been published in the United Kingdom by the Institution of Mechanical Engineers and the Royal Society. The IMechE report examined a small subset of proposed schemes (air capture, urban albedo and algal-based CO<sub>2</sub> capture schemes), and its main conclusions were that geoengineering should be researched and trialled at the small scale alongside a wider decarbonisation of the economy.

The Royal Society review examined a wide range of geoengineering schemes and evaluated them in terms of effectiveness, affordability, timeliness and safety (assigning qualitative estimates in each assessment). Similarly to Lenton and Vaughan, the report divided schemes into "carbon dioxide removal" (CDR) and "solar radiation management" (SRM) approaches that respectively address longwave and shortwave radiation. The key recommendations of the report were that "Parties to the UNFCCC should make increased efforts towards mitigating and adapting to climate change, and in particular to agreeing to global emissions reductions", and that "[nothing] now known about geoengineering options gives any reason to diminish these efforts". Nonetheless, the report also recommended that "research and development of geoengineering options should be undertaken to investigate whether low risk methods can be made available if it becomes necessary to reduce the rate of warming this century".

## Chapter-3

# Space Sunshade and Natural Satellite Habitability

## Space sunshade

A **space sunshade** or **sunshield** can be described as analogous to a parasol that diverts or otherwise reduces some of a star's rays, preventing them from hitting a planet and thereby reducing its insolation, which results in less heating of the planet.

A sunshade is of particular interest towards mitigating global warming through solar radiation management. Such shades could also be used to produce space solar power, acting as solar power satellites. Proposed shade designs include a single-piece shade and a shade made by a great number of small objects.

### ***Cloud of small spacecraft near L1***

One proposed such sunshade for use towards that effect would be composed of 16 trillion small disks at the Sun-Earth L1 Lagrangian point, 1.5 million kilometers above Earth. Each disk is proposed to have a 0.6 meter diameter and a thickness of about 5 microns. The weight of such a sunshade would be about a gram, adding up to a total weight of almost 20 million tonnes. Such a group of small sunshades that blocks 2% of the sunlight, reflecting it off into space, would be enough to halt global warming, giving us ample time to cut our emissions back on earth.

The individual autonomous flyers building up the cloud of sunshades are proposed to not reflect the sunlight but be transparent lenses, deflecting the light slightly so it does not hit earth. This minimizes the effect of solar radiation pressure on the units, requiring less effort to be put into holding them in place at the L1 point. An optical prototype has been constructed by Roger Angel with funding from NIAC.

The remaining solar pressure and the fact that the L1 point is an unstable position easily disturbed by the wobble of the earth due to gravitational effects from the moon, requires the small autonomous flyers to be capable of maneuvering themselves to keep their position. A suggested solution to this problem is the placement of mirrors capable of rotation on the surface of the flyers. By using the solar radiation pressure on the mirrors

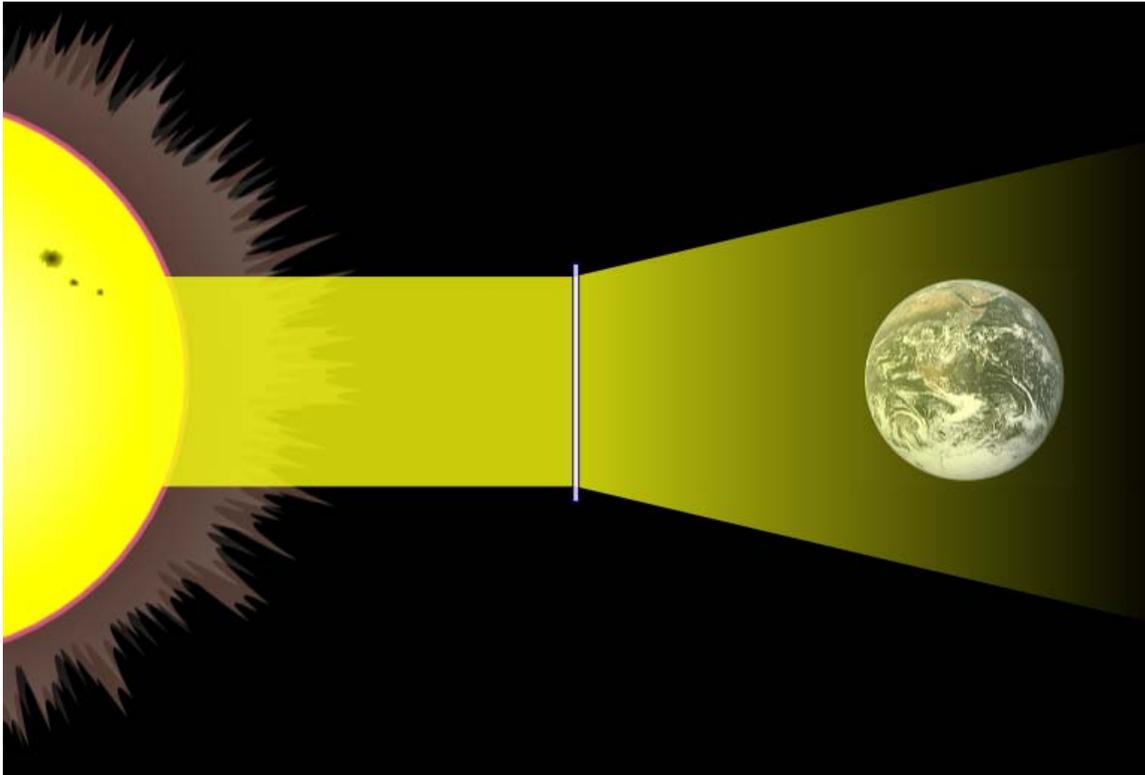
and tilting them in the right direction, the flyer will be capable of altering its speed and direction to keep in position.

Such a group of sunshades would need to occupy an area of about 3.8 square kilometers if placed at the L1 point. The deployment of the flyers is an issue that requires new technology. It has been proposed that this would be accomplished most easily with large railguns or coilguns firing a capsule containing a million shades into space every 5 minutes for 10 years using 20 separate launch sites. The esteemed total cost of such an operation is 5 trillion US dollars, with a believed lifetime of 50 years.

Even so, it would still take years to launch enough of the disks into orbit before they have any effect. Thus, if using this technology should become essential, enough time would be needed to implement it. Rebecca Shafer of Reed College presented the idea for the Sunshade at the U.S. National Academy of Sciences in April, 2006 and won a NASA Institute for Advanced Concepts grant for further research in July, 2006. Her team members working on the grant are David Miller of the Massachusetts Institute of Technology, Nick Woolf of UA's Steward Observatory, and NASA Ames Research Center Director S. Pete Worden.

Creating this sunshade in space was estimated to cost in excess of US\$5 trillion, thus leading Professor Shafer to conclude that "[t]he sunshade is no substitute for developing renewable energy, the only permanent solution. A similar massive level of technological innovation and financial investment could ensure that. But if the planet gets into an abrupt climate crisis that can only be fixed by cooling, it would be good to be ready with some shading solutions that have been worked out."

## ***Sunshade consisting of one Fresnel lens***



The basic function of a space lens to mitigate global warming. A 1000 kilometre diameter lens is sufficient, and much smaller than what is shown in this simplified image. As a Fresnel lens it would be only a few millimeters thick.

Several authors have proposed dispersing light before it reaches the Earth by putting a very large lens in space, perhaps at the L<sub>1</sub> point between the Earth and the Sun. This plan was proposed in 1989 by J. T. Early.

In 2004, physicist and science fiction author Gregory Benford calculated that a concave rotating Fresnel lens 1000 kilometres across, yet only a few millimeters thick, floating in space at the L<sub>1</sub> point, would reduce the solar energy reaching the Earth by approximately 0.5% to 1%. Side-effects include that, if this lens were built and global warming were avoided, there would be less incentive to reduce greenhouse gases, and humans might continue to produce too much carbon dioxide until it caused some other environmental catastrophe, such as a chemical change in ocean water that could be disastrous to ocean life.

The cost of such a lens has been disputed. At a global warming summit in 2004, Benford estimated that it would cost around US\$10 billion up front, and another \$10 billion in supportive cost during its lifespan. However, the mass of a 500 km radius circle with a thickness of 2mm at a density of 1 gram/cc would be 1.57 trillion kilograms. To launch that much mass into low earth orbit would require 12,362,000 Saturn V class launch vehicles, which would actually cost much more than 808.93\$ per launch. At a much more

realistic cost of 1 billion dollars per Saturn V class launch, it would cost 12.36 quadrillion dollars to launch the mass for the lens into low earth orbit. This is neglecting the mass of fuel in leo to boost the lens materials from leo to the L1 point. Accounting for the extra mass of fuel for the delta V required would approximately double the number of launches, which means the 10 billion dollar system would actually cost a minimum of 24.7 quadrillion dollars.

### ***Sunshade consisting of one diffraction grating***

A similar approach involves placing a very large diffraction grating (thin wire mesh) in space, perhaps at the L1 point between the Earth and the Sun. Such a proposal was made in 1997 by Edward Teller, Lowell Wood, and Roderick Hyde, although in 2002 these same authors argued for blocking solar radiation in the stratosphere rather than in orbit.

## **Natural satellite habitability**



Artist's impression of a hypothetical moon around a Saturn-like exoplanet that could be habitable.

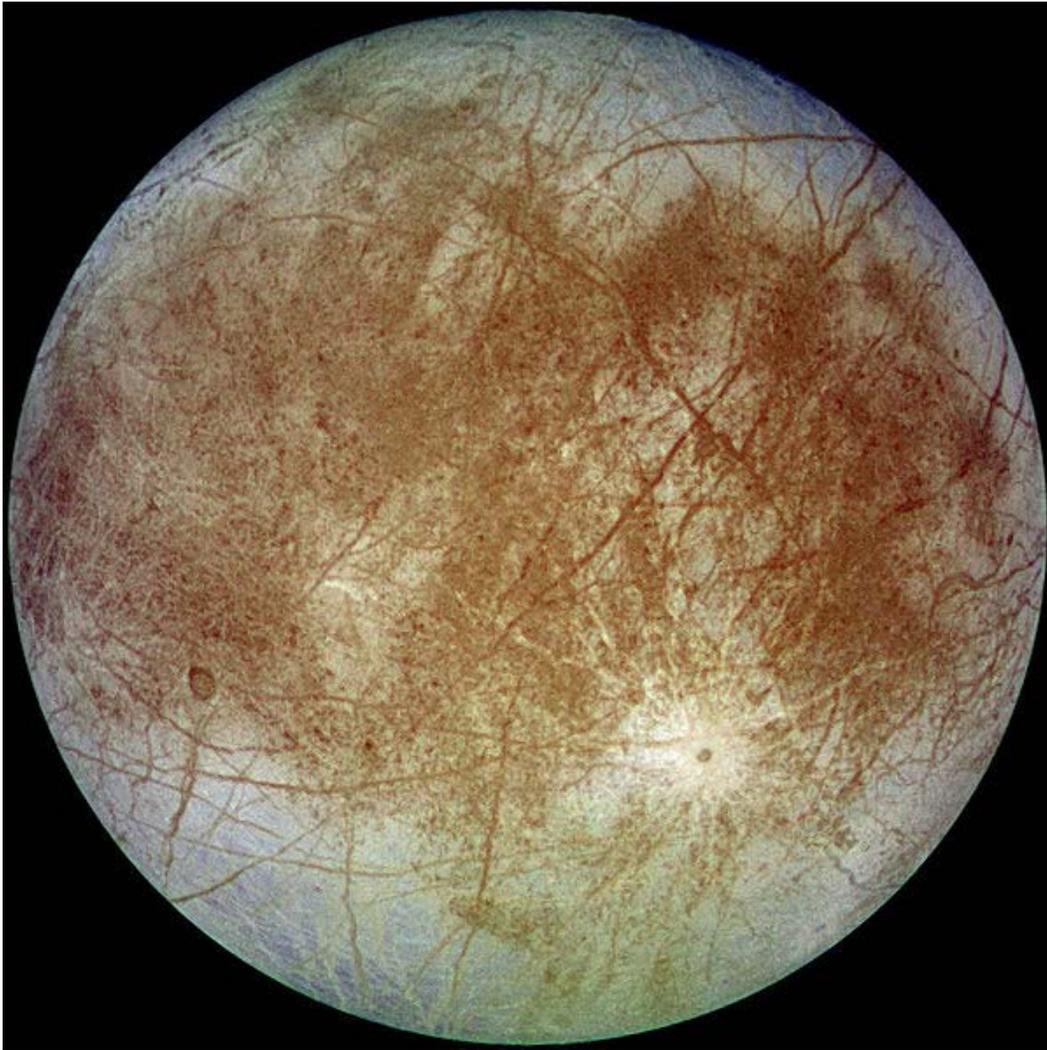
**Natural satellite habitability** is the measure of a natural satellite's potential to sustain life. Theoretical conditions under which life might on develop natural satellites (moons) are similar to those of planets. More complex orbital arrangements and differences in mass and other bulk criteria are considered by scientists in studying the possibility of habitable satellites.

Scientists generally consider the probability of extraterrestrial life on natural satellites within our own solar system to be remote given the complex conditions required for

abiogenesis. Within our solar system's habitable zone the only such objects are the moon (Luna), Phobos and Deimos and do not have either an atmosphere or water in liquid form. However several candidates have been identified that have some of the ingredients thought necessary for life to exist. The theory of panspermia suggests that life may have been introduced to such environments. The strongest such candidates are satellites of the Jupiter and Saturn. There is also the theoretical possibility of exotic biochemistries within our own solar system. No extrasolar moons are yet known to exist and there is no way of knowing how common they may be or how many could be considered habitable.

Moon habitability is sometimes used in the context of potential candidates for Space colonization by humans. Humans can inhabit moons through artificial environments and have indeed inhabited our moon (Luna) for brief periods of time. However the most Earth-like moon in our solar system is Titan, however it is extremely uninhabitable in this sense. Terraforming of moons may be possible but outside the limits of current technology. Moon habitability for terrestrial life is also a distinct possibility, through either deliberate or accidental future forward-contamination.

## ***Possible habitable moons***



Europa, a moon of Jupiter with a possibility of having life

The following is a list of satellites which are possible candidates for life in our solar system in approximate order of probability for harboring life.

<b>Name</b>	<b>System</b>	<b>Notes</b>
Europa	Jupiter	Has an ocean heated by volcanic activity, tidal energy and radiation. Also may have more water and oxygen than Earth, including an oxygen atmosphere

Enceladus	Saturn	Has water and geothermal activity
Titan	Saturn	Considered similar to an early Earth with a thicker atmosphere, hydrocarbon lakes, cryovolcanos, with a remote possibility of an exotic methane-based biochemistry
Rhea	Saturn	Has a thin atmopshere containing oxygen and carbon dioxide
Callisto	Jupiter	Thought to have a sub-surface ocean heated by radiation.
Io	Jupiter	Volcanically active, generating heat energy with a trace atmosphere
Triton	Neptune	Possible layer of liquid water or subterranean ocean.
Charon	Pluto	Possible internal ocean of water and ammonia evidenced by possible cryovolcanic activity.

### ***Conditions for habitability***

Several factors are assumed by scientists to be conditions required for a habitable moon.

#### **Stable climate**

#### **Orbital stability**

For a stable orbit (and thus a stable climate), the ratio between the moon's orbital period around its primary and that of the primary around its sun cannot be too small. Simulations suggest that a moon with an orbital period less than about 45 to 60 days will remain safely bound to a massive giant planet or brown dwarf that orbits 1 AU from a Sun-like star.

#### **Atmosphere**

A moon would need at least 7% of Earth's mass to retain most of its atmosphere for 4.6 billion years (Earth's current age) if it had a Mars-like density and an Earth-like

atmospheric temperature structure, because some of the gas atoms at the top of an atmosphere will get kicked by random thermal collisions to faster than the moon's escape velocity and fly away.

The other thing that can make a moon lose its atmosphere is sputtering, a process whereby atoms are ejected from a solid target material due to bombardment of the target by energetic particles. All the gas giants that are in our solar system, and likely others, have magnetospheres with radiation belts potent enough to completely erode an atmosphere of an earth-like moon in just a few hundred million years. One way to decrease loss of atmosphere by sputtering is for the moon to have strong magnetic field. NASA's Galileo's measurements hints large moons can have strong magnetic field. It detected Earth-like magnetic field around Ganymede even though its mass is only 2.5% of Earth's

### **Length of day**

A moon orbiting a gas giant or brown dwarf is likely to be tidally locked to its primary: that is, its day is as long as its orbit. Monoj Joshi and Robert Haberle (NASA/Ames Research Center) and their colleagues modelled the temperature on tide-locked exoplanets in the habitability zone of red dwarfs. They found that an atmosphere with a carbon-dioxide pressure of only 1 to 1.5 atmospheres not only allows habitable temperatures but allows liquid water on the dark side. The temperature range of a moon that is tidally locked to a gas giant should be less extreme than with a planet that locked to a sun. Even though no studies have been done on the subject, just modest amounts of CO<sub>2</sub> would make the temperature habitable.

## Chapter-4

# Stratospheric Sulfur Aerosols

**Stratospheric sulfur aerosols** are tiny sulfur-rich particles of solid or liquid, or a mixture of the two, which exist in the stratosphere region of the Earth's atmosphere. When present, after a strong volcanic eruption such as Mount Pinatubo, they produce a cooling effect for a few years before the particles fall out, by reflecting sunlight, and by modifying clouds as they fall out of the stratosphere.

An aerosol is a suspension of fine solid particles or liquid droplets in a gas. The sulfate particles or sulfuric acid droplets in the atmosphere are about 0.1 to 1.0 micrometer (a millionth of a meter) in diameter.

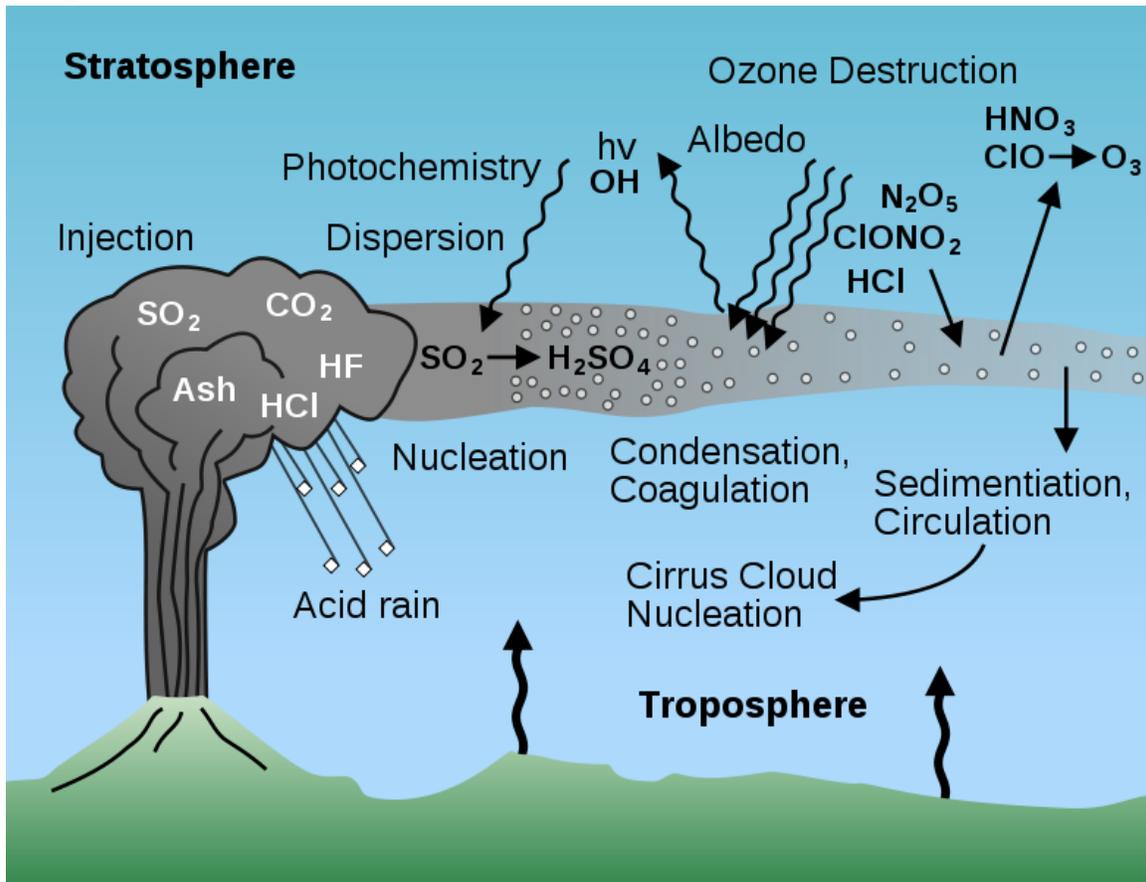
Sulfur aerosols are common in the troposphere as a result of pollution with sulfur dioxide from burning coal, and from natural processes. Volcanos are the major source of particles in the stratosphere as the force of the volcanic eruption propels sulfur-containing gases into the stratosphere.

Creating stratospheric sulfur aerosols deliberately is a proposed geoengineering technique which offers a possible solution to some of the problems caused by global warming. However, this will not be without side effects and it has been suggested that the cure may be worse than the disease.



Pinatubo eruption cloud. This volcano released huge quantities of stratospheric sulfur aerosols and contributed greatly to understanding of the subject.

## Origins



Volcanic "injection"

Natural sulfur aerosols are formed in vast quantities from the  $\text{SO}_2$  ejected by volcanoes, which may be injected directly into the stratosphere during very large (Volcanic Explosivity Index, VEI, of 4 or greater) eruptions. A comprehensive analysis, dealing largely with tropospheric sulfur compounds in the atmosphere, is provided by Bates et al.

The IPCC AR4 says *explosive volcanic events are episodic, but the stratospheric aerosols resulting from them yield substantial transitory perturbations to the radiative energy balance of the planet, with both shortwave and longwave effects sensitive to the microphysical characteristics of the aerosols*. As of 2009 there have been no explosive and climatically significant volcanic events since Mt. Pinatubo and consequently stratospheric aerosol concentrations are at the lowest concentrations since the satellite era and global coverage began in about 1980.

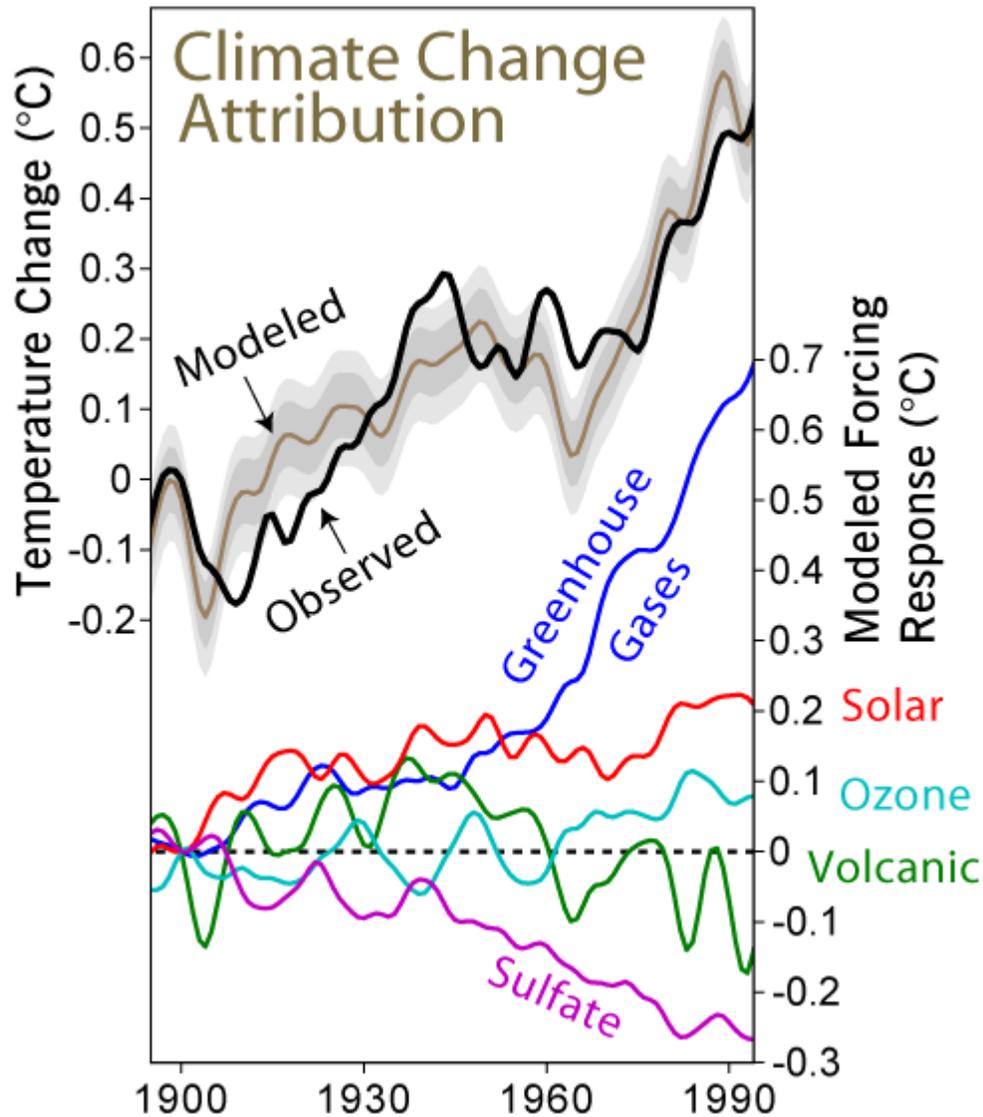
During periods lacking volcanic activity (and thus direct injection of  $\text{SO}_2$  into the stratosphere), oxidation of COS (carbonyl sulfide) dominates the production of stratospheric sulfur aerosol.

## ***Chemistry***

The chemistry of stratospheric sulfur aerosols varies significantly according to their source. Volcanic emissions vary significantly in composition, and have complex chemistry due to the presence of ash particulates and a wide variety of other elements in the plume.

The chemical reactions affecting both the formation and elimination of sulfur aerosols are not fully understood. It is difficult to estimate accurately, for example, whether the presence of ash and water vapour is important for aerosol formation from volcanic products, and whether high or low atmospheric concentrations of precursor chemicals (such as SO<sub>2</sub> and H<sub>2</sub>S) are optimal for aerosol formation. This uncertainty makes it difficult to determine a viable approach for geoengineering uses of sulfur aerosol formation.

## Scientific study



Stratospheric sulfates from volcanic emissions cause transient cooling; the purple line showing sustained cooling is from tropospheric sulfate

Understanding of these aerosols comes in large part from the study of volcanic eruptions, notably Mount Pinatubo in the Philippines, which erupted in 1991 when scientific techniques were sufficiently far advanced to study the effects carefully.

The formation of the aerosols and their effects on the atmosphere can also be studied in the lab. Samples of actual particles can be recovered from the stratosphere using balloons or aircraft.

Computer models can be used to understand the behaviour of aerosol particles, and are particularly useful in modelling their effect on global climate.

Biological experiments in the lab, and field/ocean measurements can establish the formation mechanisms of biologically derived volatile sulfurous gases.

## ***Effects***

### **Effect on climate**

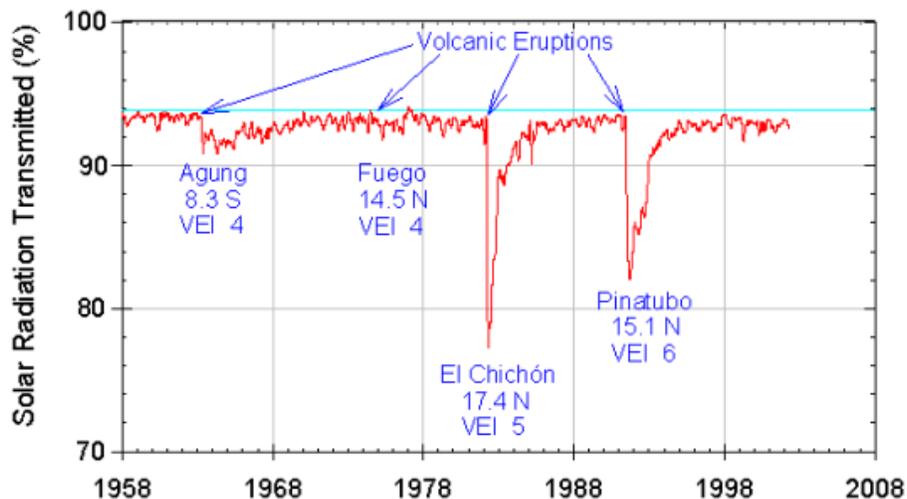
It has been established that emission of precursor gases for sulfur aerosols is the principle mechanism by which volcanoes cause episodic global cooling.

The Intergovernmental Panel on Climate Change AR4 regards stratospheric sulfate aerosols as having a low level of scientific understanding.

The aerosol particles form a whitish haze in the sky. This creates a global dimming effect, where less of the sun's radiation is able to reach the surface of the Earth. This leads to a global cooling effect. In essence, they act as the reverse of a greenhouse gas, which tends to allow visible light from the sun through, whilst blocking infra-red emitted from the Earth's surface and its atmosphere. The particles also radiate infra red energy directly, as they lose heat into space.

### ***Effects on light transmission through the atmosphere***

#### **Mauna Loa Observatory Atmospheric Transmission**



Solar radiation reduction due to volcanic eruptions

All aerosols both absorb and scatter solar and terrestrial radiation. This is quantified in the *Single Scattering Albedo* (SSA), the ratio of scattering alone to scattering plus absorption (*extinction*) of radiation by a particle. The SSA tends to unity if scattering dominates, with relatively little absorption, and decreases as absorption increases, becoming zero for infinite absorption. For example, sea-salt aerosol has an SSA of 1, as a sea-salt particle only scatters, whereas soot has an SSA of 0.23, showing that it is a major atmospheric aerosol absorber.

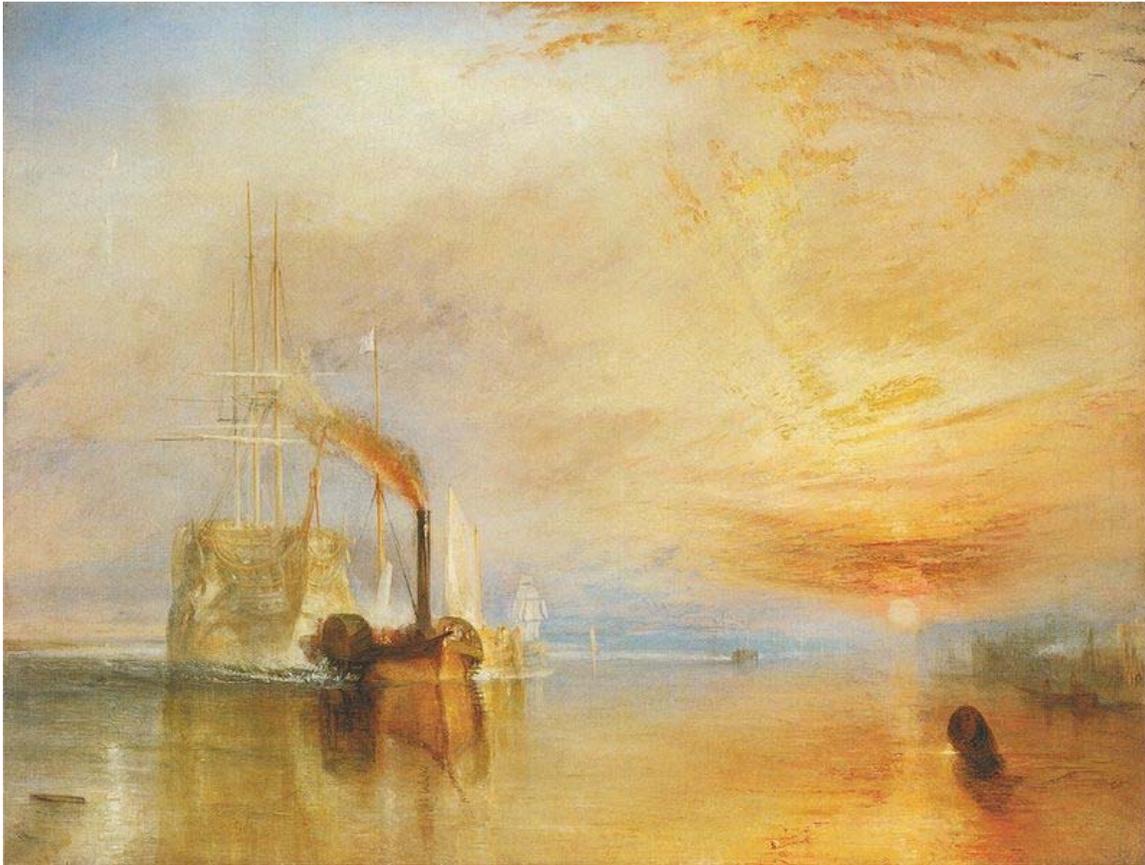
Aerosols, natural and anthropogenic, can affect the climate by changing the way radiation is transmitted through the atmosphere. Direct observations of the effects of aerosols are quite limited so any attempt to estimate their global effect necessarily involves the use of computer models. The Intergovernmental Panel on Climate Change, IPCC, says: *While the radiative forcing due to greenhouse gases may be determined to a reasonably high degree of accuracy... the uncertainties relating to aerosol radiative forcings remain large, and rely to a large extent on the estimates from global modelling studies that are difficult to verify at the present time.* However, they are mostly talking about tropospheric aerosol.

### **Effect on ozone**

The aerosols have a role in the destruction of ozone due to surface chemistry effects. Destruction of ozone has in recent years created large holes in the ozone layer, initially over the Antarctic and then the Arctic. These holes in the ozone layer have the potential to expand to cover inhabited and vegetative regions of the planet, leading to catastrophic environmental damage.

Ozone destruction occurs principally in polar regions, but the formation of ozone occurs principally in the tropics. Ozone is distributed around the planet by the Brewer-Dobson circulation. Therefore, the source and dispersal pattern of aerosols is critical in understanding their effect on the ozone layer.

## Effect on sky appearance



Turner was inspired by dramatic sunsets caused by volcanic aerosols.

Aerosols scatter light, which affects the appearance of the sky and of sunsets. Changing the concentration of aerosols in the atmosphere can dramatically affect the appearance of sunsets. A change in sky appearance during the year without a summer (attributed to the eruption of Tambora) was the inspiration for the paintings of J. M. W. Turner. Further volcanic eruptions and geoengineering projects involving sulfur aerosols are likely to affect the appearance of sunsets significantly, and to create a haze in the sky.

## Effect on the biosphere

Aerosol particles are eventually deposited from the stratosphere onto land and ocean. Depending on the volume of particles descending, the effects may be significant to ecosystems, or may not be. Modelling of the quantities of aerosols used in likely geoengineering scenarios suggest that effects on terrestrial ecosystems from deposition is not likely to be significantly harmful.

## ***Geoengineering***

The ability of stratospheric sulfur aerosols to create this global dimming effect has made them a possible candidate for use in geoengineering projects to limit the effect and impact of climate change due to rising levels of greenhouse gases. Delivery of precursor gases such as H<sub>2</sub>S and SO<sub>2</sub> by artillery, aircraft and balloons has been proposed.

Understanding of this proposed technique is partly based on the fact that it is the adaptation of an existing atmospheric process. The technique is therefore potentially better understood than are comparable (but purely speculative) geoengineering schemes. It is also partly based on the speed of action of any such solution deployed, in contrast to carbon sequestration projects such as carbon dioxide air capture which would take longer to work. However, gaps in understanding of these processes exist, for example the effect on stratospheric climate and on rainfall patterns, and further research is needed.

This technique has been studied more extensively than most other geoengineering techniques, and is suggested by commentators including Tom Wigley.

## Chapter-5

# Planetary Habitability



Understanding planetary habitability is partly an extrapolation of the Earth's conditions, as it is the only planet currently known to support life

**Planetary habitability** is the measure of a planet's or a natural satellite's potential to sustain life. Life may develop directly on a planet or satellite or be transferred to it from another body, a theoretical process known as panspermia. As the existence of life beyond Earth is currently uncertain, planetary habitability is largely an extrapolation of conditions on Earth and the characteristics of the Sun and solar system which appear

favorable to life's flourishing—in particular those factors that have sustained complex, multicellular organisms and not just simpler, unicellular creatures. Research and theory in this regard is a component of planetary science and the emerging discipline of astrobiology.

An absolute requirement for life is an energy source, and the notion of planetary habitability implies that many other geophysical, geochemical, and astrophysical criteria must be met before an astronomical body can support life. In its astrobiology roadmap, NASA has defined the principal habitability criteria as "extended regions of liquid water, conditions favorable for the assembly of complex organic molecules, and energy sources to sustain metabolism."

In determining the habitability potential of a body, studies focus on its bulk composition, orbital properties, atmosphere, and potential chemical interactions. Stellar characteristics of importance include mass and luminosity, stable variability, and high metallicity. Rocky, terrestrial-type planets and moons with the potential for Earth-like chemistry are a primary focus of astrobiological research, although more speculative habitability theories occasionally examine alternative biochemistries and other types of astronomical bodies.

The idea that planets beyond Earth might host life is an ancient one, though historically it was framed by philosophy as much as physical science.<sup>a</sup> The late 20th century saw two breakthroughs in the field. The observation and robotic spacecraft exploration of other planets and moons within the solar system has provided critical information on defining habitability criteria and allowed for substantial geophysical comparisons between the Earth and other bodies. The discovery of extrasolar planets, beginning in the early 1990s and accelerating thereafter, has provided further information for the study of possible extraterrestrial life. These findings confirm that the Sun is not unique among stars in hosting planets and expands the habitability research horizon beyond our own solar system.

### ***Suitable star systems***

An understanding of planetary habitability begins with stars. While bodies that are generally Earth-like may be plentiful, it is just as important that their larger system be agreeable to life. Under the auspices of SETI's Project Phoenix, scientists Margaret Turnbull and Jill Tarter developed the "HabCat" (or Catalogue of Habitable Stellar Systems) in 2002. The catalogue was formed by winnowing the nearly 120,000 stars of the larger Hipparcos Catalogue into a core group of 17,000 "HabStars," and the selection criteria that were used provide a good starting point for understanding which astrophysical factors are necessary to habitable planets.

### **Spectral class**

The spectral class of a star indicates its photospheric temperature, which (for main-sequence stars) correlates to overall mass. The appropriate spectral range for "HabStars" is presently considered to be "early F" or "G", to "mid-K". This corresponds to

temperatures of a little more than 7,000 K down to a little more than 4,000 K; the Sun, a G2 star, is well within these bounds. "Middle-class" stars of this sort have a number of characteristics considered important to planetary habitability:

- They live at least a few billion years, allowing life a chance to evolve. More luminous main-sequence stars of the "O," "B," and "A" classes usually live less than a billion years and in exceptional cases less than 10 million.<sup>b</sup>
- They emit enough high-frequency ultraviolet radiation to trigger important atmospheric dynamics such as ozone formation, but not so much that ionisation destroys incipient life.
- Liquid water may exist on the surface of planets orbiting them at a distance that does not induce tidal lock. K Spectrum stars may be able to support life for long periods, far longer than our sun.

This spectral range probably accounts for between 5% and 10% of stars in the local Milky Way galaxy. Whether fainter late K and M class red dwarf stars are also suitable hosts for habitable planets is perhaps the most important open question in the entire field of planetary habitability given their ubiquity (habitability of red dwarf systems). Gliese 581 c, a "super-Earth," has been found orbiting in the "habitable zone" of a red dwarf and may possess liquid water. Alternately, a greenhouse effect may render it too hot to support life, while its neighbor, Gliese 581 d, may in fact be a more likely candidate for habitability. In September 2010, the discovery was announced of another planet in an orbit between these two planets.

## **A stable habitable zone**

The habitable zone (HZ) is a theoretical shell surrounding a star in which any planet present would have liquid water on its surface. After an energy source, liquid water is considered the most important ingredient for life, considering how integral it is to all life-systems on Earth. This may reflect the bias of humanity's water-dependent biology, however, and if life is discovered in the absence of water (for example, in a liquid-ammonia solution), the notion of an HZ may have to be greatly expanded or else discarded altogether as too restricting.<sup>c</sup>

A "stable" HZ denotes two factors. First, the range of an HZ should not vary greatly over time. All stars increase in luminosity as they age and a given HZ naturally migrates outwards, but if this happens too quickly (for example, with a super-massive star), planets may only have a brief window inside the HZ and a correspondingly weaker chance to develop life. Calculating an HZ range and its long-term movement is never straightforward, given that negative feedback loops such as the carbon cycle will tend to offset the increases in luminosity. Assumptions made about atmospheric conditions and geology thus have as great an impact on a putative HZ range as does Solar evolution; the proposed parameters of the Sun's HZ, for example, have fluctuated greatly.

Secondly, no large-mass body such as a gas giant should be present in or relatively close to the HZ, thus disrupting the formation of Earth-like bodies. The mass of the asteroid

belt, for example, appears to have been unable to accrete into a planet due to orbital resonances with Jupiter; if the giant had appeared in the region that is now between the orbits of Venus and Mars, Earth would almost certainly not have developed its present form. This is somewhat ameliorated by suggestions that a gas giant inside the HZ might have habitable moons under the right conditions.

In the Solar System, the inner planets are terrestrial, the outer ones gas giants, but discoveries of extrasolar planets suggest this arrangement may not be at all common: numerous Jupiter-sized bodies have been found in close orbit about their primary, disrupting potential HZs. However, present data for extrasolar planets is likely to be skewed towards these types (large planets in close orbits) because they are far easier to identify; thus, it remains to be seen which type of planetary system is the norm, or indeed if there is one.

### **Low stellar variation**

Changes in luminosity are common to all stars, but the severity of such fluctuations covers a broad range. Most stars are relatively stable, but a significant minority of variable stars often experience sudden and intense increases in luminosity and consequently the amount of energy radiated toward bodies in orbit. These are considered poor candidates for hosting life-bearing planets as their unpredictability and energy output changes would negatively impact organisms. Particularly, living things adapted to a specific temperature range would probably be unable to survive too great a temperature deviation. Further, upswings in luminosity are generally accompanied by massive doses of gamma ray and X-ray radiation which might prove lethal. Atmospheres do mitigate such effects, but atmosphere retention might not occur on planets orbiting variables, because the high-frequency energy buffeting these bodies would continually strip them of their protective covering.

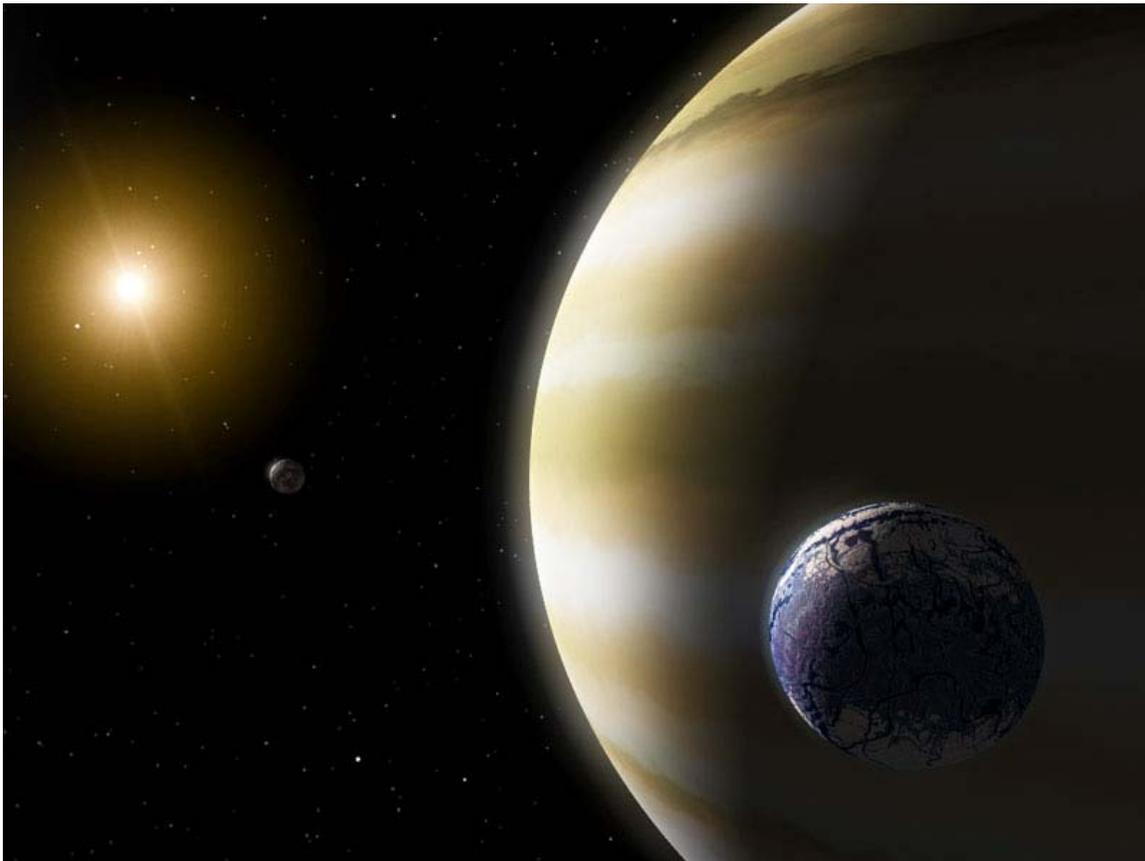
The Sun, as in much else, is benign in terms of this danger: the variation between solar max and minimum is roughly 0.1% over its 11-year solar cycle. There is strong (though not undisputed) evidence that even minor changes in the Sun's luminosity have had significant effects on the Earth's climate well within the historical era; the Little Ice Age of the mid-second millennium, for instance, may have been caused by a relatively long-term decline in the Sun's luminosity. Thus, a star does not have to be a true variable for differences in luminosity to affect habitability. Of known "solar analogs," the one that most closely resembles the Sun is considered to be 18 Scorpii; unfortunately for the prospects of life existing in its proximity, the only significant difference between the two bodies is the amplitude of the solar cycle, which appears to be much greater for 18 Scorpii.

### **High metallicity**

While the bulk of material in any star is hydrogen and helium, there is a great variation in the amount of heavier elements (metals) stars contain. A high proportion of metals in a star correlates to the amount of heavy material initially available in protoplanetary disks.

A low amount of metal significantly decreases the probability that planets will have formed around that star, under the solar nebula theory of planetary systems formation. Any planets that did form around a metal-poor star would probably be low in mass, and thus unfavorable for life. Spectroscopic studies of systems where exoplanets have been found to date confirm the relationship between high metal content and planet formation: "stars with planets, or at least with planets similar to the ones we are finding today, are clearly more metal rich than stars without planetary companions." High metallicity also places a requirement for youth on hab-stars: stars formed early in the universe's history have low metal content and a correspondingly lesser likelihood of having planetary companions.

### ***Planetary characteristics***



The moons of some gas giants could potentially be habitable.

The chief assumption about habitable planets is that they are terrestrial. Such planets, roughly within one order of magnitude of Earth mass, are primarily composed of silicate rocks and have not accreted the gaseous outer layers of hydrogen and helium found on gas giants. That life could evolve in the cloud tops of giant planets has not been decisively ruled out,<sup>d</sup> though it is considered unlikely given that they have no surface and their gravity is enormous. The natural satellites of giant planets, meanwhile, remain perfectly valid candidates for hosting life.

In February 2011 the Kepler Space Observatory Mission team released a list of 1235 extrasolar planet candidates, including 54 that may be in the habitable zone. Six of the candidates in this zone are smaller than twice the size of Earth. A more recent study found that one of these candidates (KOI 326.01) is in fact much larger and hotter than first reported. Based on the findings, the Kepler Team has estimated "at least 50 billion planets in the Milky Way" of which "at least 500 million" are in the habitable zone.

In analyzing which environments are likely to support life, a distinction is usually made between simple, unicellular organisms such as bacteria and archaea and complex metazoans (animals). Unicellularity necessarily precedes multicellularity in any hypothetical tree of life and where single-celled organisms do emerge there is no assurance that this will lead to greater complexity.<sup>e</sup> The planetary characteristics listed below are considered crucial for life generally, but in every case habitability impediments should be considered greater for multicellular organisms such as plants and animals versus unicellular life.

## **Mass**



Mars, with its rarefied atmosphere, is colder than the Earth would be, if it were at a similar distance from the Sun

Low-mass planets are poor candidates for life for two reasons. First, their lesser gravity makes atmosphere retention difficult. Constituent molecules are more likely to reach escape velocity and be lost to space when buffeted by solar wind or stirred by collision. Planets without a thick atmosphere lack the matter necessary for primal biochemistry, have little insulation and poor heat transfer across their surfaces (for example, Mars, with its thin atmosphere, is colder than the Earth would be if it were at a similar distance from the sun), and provide less protection against meteoroids and high-frequency radiation. Further, where an atmosphere is less than 0.006 Earth atmospheres, water cannot exist in liquid form as the required atmospheric pressure, 4.56 mm Hg (608 Pa) (0.18 inch Hg), does not occur. The temperature range at which water is liquid is smaller at low pressures generally.

Secondly, smaller planets have smaller diameters and thus higher surface-to-volume ratios than their larger cousins. Such bodies tend to lose the energy left over from their formation quickly and end up geologically dead, lacking the volcanoes, earthquakes and tectonic activity which supply the surface with life-sustaining material and the atmosphere with temperature moderators like carbon dioxide. Plate tectonics appear particularly crucial, at least on Earth: not only does the process recycle important chemicals and minerals, it also fosters bio-diversity through continent creation and increased environmental complexity and helps create the convective cells necessary to generate Earth's magnetic field.

"Low mass" is partly a relative label; the Earth is considered low mass when compared to the Solar System's gas giants, but it is the largest, by diameter and mass, and densest of all terrestrial bodies.<sup>f</sup> It is large enough to retain an atmosphere through gravity alone and large enough that its molten core remains a heat engine, driving the diverse geology of the surface (the decay of radioactive elements within a planet's core is the other significant component of planetary heating). Mars, by contrast, is nearly (or perhaps totally) geologically dead and has lost much of its atmosphere. Thus, it would be fair to infer that the lower mass limit for habitability lies somewhere between that of Mars and Earth or Venus; 0.3 Earth masses has been offered as a rough dividing line for habitable planets. However, a 2008 study by the Harvard-Smithsonian Center for Astrophysics suggests that the dividing line may be higher. Earth may in fact lie on the lower boundary of habitability, since if it were any smaller, plate tectonics would be impossible. Venus, which has 85 percent Earth's mass, shows no signs of tectonic activity. Conversely, "super-Earths", terrestrial planets with higher masses than Earth, would have higher levels of plate tectonics and thus be firmly placed in the habitable range. Exceptional circumstances do offer exceptional cases: Jupiter's moon Io (which is smaller than any of the terrestrial planets) is volcanically dynamic because of the gravitational stresses induced by its orbit, and its neighbor Europa may have a liquid ocean underneath a frozen shell also due to power generated from orbiting a gas giant. Saturn's Titan, meanwhile, has an outside chance of harbouring life, as it has retained a thick atmosphere and biochemical reactions are possible in the liquid methane on its surface. These satellites are exceptions, but they prove that mass as a habitability criterion cannot be considered definitive.

Finally, a larger planet is likely to have a large iron core. This allows for a magnetic field to protect the planet from stellar wind and cosmic radiation, which otherwise would tend to strip away planetary atmosphere and to bombard living things with ionized particles. Mass is not the only criterion for producing a magnetic field—as the planet must also rotate fast enough to produce a dynamo effect within its core—but it is a significant component of the process.

## **Orbit and rotation**

As with other criteria, stability is the critical consideration in determining the effect of orbital and rotational characteristics on planetary habitability. Orbital eccentricity is the difference between a planet's farthest and closest approach to its parent star divided by

the sum of said distances. It is a ratio describing the shape of the elliptical orbit. The greater the eccentricity the greater the temperature fluctuation on a planet's surface. Although they are adaptive, living organisms can only stand so much variation, particularly if the fluctuations overlap both the freezing point and boiling point of the planet's main biotic solvent (e.g., water on Earth). If, for example, Earth's oceans were alternately boiling and freezing solid, it is difficult to imagine life as we know it having evolved. The more complex the organism, the greater the temperature sensitivity. The Earth's orbit is almost wholly circular, with an eccentricity of less than 0.02; other planets in our solar system (with the exception of Mercury) have eccentricities that are similarly benign.

Data collected on the orbital eccentricities of extrasolar planets has surprised most researchers: 90% have an orbital eccentricity greater than that found within the solar system, and the average is fully 0.25.

A planet's movement around its rotational axis must also meet certain criteria if life is to have the opportunity to evolve. A first assumption is that the planet should have moderate seasons. If there is little or no axial tilt (or obliquity) relative to the perpendicular of the ecliptic, seasons will not occur and a main stimulant to biospheric dynamism will disappear. The planet would also be colder than it would be with a significant tilt: when the greatest intensity of radiation is always within a few degrees of the equator, warm weather cannot move poleward and a planet's climate becomes dominated by colder polar weather systems.

If a planet is radically tilted, meanwhile, seasons will be extreme and make it more difficult for a biosphere to achieve homeostasis. Although during the Quaternary higher axial tilt of the Earth coincides with reduced polar ice, warmer temperatures and *less* seasonal variation, scientists do not know whether this trend would continue indefinitely with further increases in axial tilt.

The exact effects of these changes can only be computer modelled at present, and studies have shown that even extreme tilts of up to 85 degrees do not absolutely preclude life "provided it does not occupy continental surfaces plagued seasonally by the highest temperature." Not only the mean axial tilt, but also its variation over time must be considered. The Earth's tilt varies between 21.5 and 24.5 degrees over 41,000 years. A more drastic variation, or a much shorter periodicity, would induce climatic effects such as variations in seasonal severity.

Other orbital considerations include:

- The planet should rotate relatively quickly so that the day-night cycle is not overlong. If a day takes years, the temperature differential between the day and night side will be pronounced, and problems similar to those noted with extreme orbital eccentricity will come to the fore.
- The planet should also rotate quickly enough so that a magnetic dynamo may be started in its iron core to produce a magnetic field.

- Change in the direction of the axis rotation (precession) should not be pronounced. In itself, precession need not affect habitability as it changes the direction of the tilt, not its degree. However, precession tends to accentuate variations caused by other orbital deviations. Precession on Earth occurs over a 26,000 year cycle.

The Earth's Moon appears to play a crucial role in moderating the Earth's climate by stabilising the axial tilt. It has been suggested that a chaotic tilt may be a "deal-breaker" in terms of habitability— i.e. a satellite the size of the moon is not only helpful but required to produce stability. This position remains controversial.<sup>g</sup>

## Geochemistry

It is generally assumed that any extraterrestrial life that might exist will be based on the same fundamental biochemistry as found on Earth, as the four elements most vital for life, carbon, hydrogen, oxygen, and nitrogen, are also the most common chemically reactive elements in the universe. Indeed, simple biogenic compounds, such as amino acids, have been found in meteorites and in the interstellar medium. These four elements together comprise over 96% of Earth's collective biomass. Carbon has an unparalleled ability to bond with itself and to form a massive array of intricate and varied structures, making it an ideal material for the complex mechanisms that form living cells. Hydrogen and oxygen, in the form of water, compose the solvent in which biological processes take place and in which the first reactions occurred that led to life's emergence. The energy released in the formation of powerful covalent bonds between carbon and oxygen, available by oxidizing organic compounds, is the fuel of all complex life-forms. These four elements together make up amino acids, which in turn are the building blocks of proteins, the substance of living tissue. In addition, neither sulfur, required for the building of proteins, nor phosphorus, needed for the formation of DNA, RNA, and the adenosine phosphates essential to metabolism, are rare.

Relative abundance in space does not always mirror differentiated abundance within planets; of the four life elements, for instance, only oxygen is present in any abundance in the Earth's crust. This can be partly explained by the fact that many of these elements, such as hydrogen and nitrogen, along with their simplest and most common compounds, such as carbon dioxide, carbon monoxide, methane, ammonia, and water, are gaseous at warm temperatures. In the hot region close to the Sun, these volatile compounds could not have played a significant role in the planets' geological formation. Instead, they were trapped as gases underneath the newly formed crusts, which were largely made of rocky, involatile compounds such as silica (a compound of silicon and oxygen, accounting for oxygen's relative abundance). Outgassing of volatile compounds through the first volcanoes would have contributed to the formation of the planets' atmospheres. The Miller-Urey experiment showed that, with the application of energy, amino acids can form from the synthesis of the simple compounds within a primordial atmosphere.

Even so, volcanic outgassing could not have accounted for the amount of water in Earth's oceans. The vast majority of the water—and arguably carbon— necessary for life must

have come from the outer solar system, away from the Sun's heat, where it could remain solid. Comets impacting with the Earth in the Solar system's early years would have deposited vast amounts of water, along with the other volatile compounds life requires (including amino acids) onto the early Earth, providing a kick-start to the origin of life.

Thus, while there is reason to suspect that the four "life elements" ought to be readily available elsewhere, a habitable system probably also requires a supply of long-term orbiting bodies to seed inner planets. Without comets there is a possibility that life as we know it would not exist on Earth.

### **Microenvironments and extremophiles**



The Atacama Desert provides an analog to Mars and an ideal environment to study the boundary between sterility and habitability.

One important qualification to habitability criteria is that only a tiny portion of a planet is required to support life. Astrobiologists often concern themselves with "micro-environments," noting that "we lack a fundamental understanding of how evolutionary forces, such as mutation, selection, and genetic drift, operate in micro-organisms that act on and respond to changing micro-environments." Extremophiles are Earth organisms that live in niche environments under severe conditions generally considered inimical to life. Usually (although not always) unicellular, extremophiles include acutely alkaliphilic and acidophilic organisms and others that can survive water temperatures above 100 °C in hydrothermal vents.

The discovery of life in extreme conditions has complicated definitions of habitability, but also generated much excitement amongst researchers in greatly broadening the known range of conditions under which life can persist. For example, a planet that might otherwise be unable to support an atmosphere given the solar conditions in its vicinity, might be able to do so within a deep shadowed rift or volcanic cave. Similarly, craterous terrain might offer a refuge for primitive life. The Lawn Hill crater has been studied as an astrobiological analog, with researchers suggesting rapid sediment infill created a protected microenvironment for microbial organisms; similar conditions may have occurred over the geological history of Mars.

Earth environments that *cannot* support life are still instructive to astrobiologists in defining the limits of what organisms can endure. The heart of the Atacama desert, generally considered the driest place on Earth, appears unable to support life, but it has been subject to study by NASA for that reason: it provides a Mars analog and the moisture gradients along its edges are ideal for studying the boundary between sterility and habitability. The Atacama was the subject of study in 2003 that partly replicated experiments from the Viking landings on Mars in the 1970s; no DNA could be recovered from two soil samples, and incubation experiments were also negative for biosignatures.

## ***Alternative star systems***

In determining the feasibility of extraterrestrial life, astronomers had long focused their attention on stars like our own Sun. However, they have begun to explore the possibility that life might form in systems very unlike our own.

## **Binary systems**

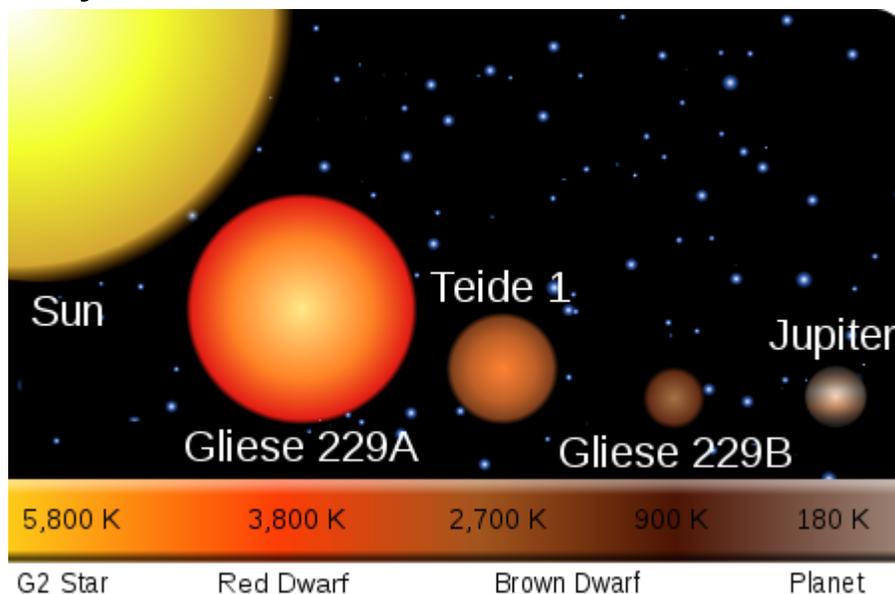
Typical estimates often suggest that 50% or more of all stellar systems are binary systems. This may be partly sample bias, as massive and bright stars tend to be in binaries and these are most easily observed and catalogued; a more precise analysis has suggested that the more common fainter stars are usually singular, and that up to two thirds of all stellar systems are therefore solitary.

The separation between stars in a binary may range from less than one astronomical unit (AU, the Earth-Sun distance) to several hundred. In latter instances, the gravitational effects will be negligible on a planet orbiting an otherwise suitable star and habitability

potential will not be disrupted unless the orbit is highly eccentric. However, where the separation is significantly less, a stable orbit may be impossible. If a planet's distance to its primary exceeds about one fifth of the closest approach of the other star, orbital stability is not guaranteed. Whether planets might form in binaries at all had long been unclear, given that gravitational forces might interfere with planet formation. Theoretical work by Alan Boss at the Carnegie Institution has shown that gas giants can form around stars in binary systems much as they do around solitary stars.

One study of Alpha Centauri, the nearest star system to the Sun, suggested that binaries need not be discounted in the search for habitable planets. Centauri A and B have an 11 AU distance at closest approach (23 AU mean), and both should have stable habitable zones. A study of long-term orbital stability for simulated planets within the system shows that planets within approximately three AU of either star may remain stable (i.e. the semi-major axis deviating by less than 5%). The HZ for Centauri A is conservatively estimated at 1.2 to 1.3 AU and Centauri B at 0.73 to 0.74—well within the stable region in both cases.

### Red dwarf systems



Relative star sizes and photospheric temperatures. Any planet around a red dwarf such as the one shown here would have to huddle close to achieve Earth-like temperatures, probably inducing tidal lock.

Determining the habitability of red dwarf stars could help determine how common life in the universe might be, as red dwarfs make up between 70 to 90% of all the stars in the galaxy. Brown dwarfs are probably more numerous than red dwarfs. However, they are not generally classified as stars, and could never support life as we understand it, since what little heat they emit quickly disappears.

Astronomers for many years ruled out red dwarfs as potential abodes for life. Their small size (from 0.1 to 0.6 solar masses) means that their nuclear reactions proceed exceptionally slowly, and they emit very little light (from 3% of that produced by the Sun to as little as 0.01%). Any planet in orbit around a red dwarf would have to huddle very close to its parent star to attain Earth-like surface temperatures; from 0.3 AU (just inside the orbit of Mercury) for a star like Lacaille 8760, to as little as 0.032 AU for a star like Proxima Centauri (such a world would have a year lasting just 6.3 days). At those distances, the star's gravity would cause tidal lock. One side of the planet would eternally face the star, while the other would always face away from it. The only way potential life could avoid either an inferno or a deep freeze would be if the planet had an atmosphere thick enough to transfer the star's heat from the day side to the night side. It was long assumed that such a thick atmosphere would prevent sunlight from reaching the surface in the first place, preventing photosynthesis.

This pessimism has been tempered by research. Studies by Robert Haberle and Manoj Joshi of NASA's Ames Research Center in California have shown that a planet's atmosphere (assuming it included greenhouse gases CO<sub>2</sub> and H<sub>2</sub>O) need only be 100 mbs, or 10% of Earth's atmosphere, for the star's heat to be effectively carried to the night side. This is well within the levels required for photosynthesis, though water would still remain frozen on the dark side in some of their models. Martin Heath of Greenwich Community College, has shown that seawater, too, could be effectively circulated without freezing solid if the ocean basins were deep enough to allow free flow beneath the night side's ice cap. Further research—including a consideration of the amount of photosynthetically active radiation—suggested that tidally locked planets in red dwarf systems might at least be habitable for higher plants.

Size is not the only factor in making red dwarfs potentially unsuitable for life, however. On a red dwarf planet, photosynthesis on the night side would be impossible, since it would never see the sun. On the day side, because the sun does not rise or set, areas in the shadows of mountains would remain so forever. Photosynthesis as we understand it would be complicated by the fact that a red dwarf produces most of its radiation in the infrared, and on the Earth the process depends on visible light. There are potential positives to this scenario. Numerous terrestrial ecosystems rely on chemosynthesis rather than photosynthesis, for instance, which would be possible in a red dwarf system. A static primary star position removes the need for plants to steer leaves toward the sun, deal with changing shade/sun patterns, or change from photosynthesis to stored energy during night. Because of the lack of a day-night cycle, including the weak light of morning and evening, far more energy would be available at a given radiation level.

Red dwarfs are far more variable and violent than their more stable, larger cousins. Often they are covered in starspots that can dim their emitted light by up to 40% for months at a time, while at other times they emit gigantic flares that can double their brightness in a matter of minutes. Such variation would be very damaging for life, as it would not only destroy any complex organic molecules that could possibly form biological precursors, but also because it would blow off sizeable portions of the planet's atmosphere. For a planet around a red dwarf star to support life, it would require a rapidly rotating magnetic

field to protect it from the flares. However, a tidally locked planet rotates only very slowly, and so cannot produce a geodynamo at its core. However, the violent flaring period of a red dwarf's life cycle is estimated to only last roughly the first 1.2 billion years of its existence. If a planet forms far away from a red dwarf so as to avoid tidal locking, and then migrates into the star's habitable zone after this turbulent initial period, it is possible that life may have a chance to develop.

There is, however, one major advantage that red dwarfs have over other stars as abodes for life: they live a long time. It took 4.5 billion years before humanity appeared on Earth, and life as we know it will see suitable conditions for at most 1 billion years more. Red dwarfs, by contrast, could live for trillions of years because their nuclear reactions are far slower than those of larger stars, meaning that life would have longer to evolve and survive. Further, while the odds of finding a planet in the habitable zone around any specific red dwarf are slim, the total amount of habitable zone around all red dwarfs combined is equal to the total amount around Sun-like stars given their ubiquity.

## **Massive stars**

Recent research suggests that very large stars, greater than ~100 solar masses, could have planetary systems consisting of hundreds of Mercury-sized planets within the habitable zone. Such systems could also contain brown dwarfs and low-mass stars (~0.1-0.3 solar masses).

## ***The galactic neighborhood***

Along with the characteristics of planets and their star systems, the wider galactic environment may also impact habitability. Scientists considered the possibility that particular areas of galaxies (galactic habitable zones) are better suited to life than others; the solar system in which we live, in the Orion Spur, on the Milky Way galaxy's edge is considered to be in a life-favorable spot:

- It is not in a globular cluster where immense star densities are inimical to life, given excessive radiation and gravitational disturbance. Globular clusters are also primarily composed of older, probably metal-poor, stars.
- It is not near an active gamma ray source.
- It is not near the galactic center where once again star densities increase the likelihood of ionizing radiation (e.g., from magnetars and supernovae). A supermassive black hole is also believed to lie at the middle of the galaxy which might prove a danger to any nearby bodies.
- The circular orbit of the Sun around the galactic center keeps it out of the way of the galaxy's spiral arms where once more intense radiation and gravitation may lead to disruption.

Thus, relative loneliness is ultimately what a life-bearing system needs. If the Sun were crowded amongst other systems, the chance of being fatally close to dangerous radiation sources would increase significantly. Further, close neighbours might disrupt the stability

of various orbiting bodies such as Oort cloud and Kuiper Belt objects, which can bring catastrophe if knocked into the inner solar system.

While stellar crowding proves disadvantageous to habitability, so too does extreme isolation. A star as metal-rich as the Sun would probably not have formed in the very outermost regions of the Milky Way given a decline in the relative abundance of metals and a general lack of star formation. Thus, a "suburban" location, such as our Solar System enjoys, is preferable to a Galaxy's center or farthest reaches.

## ***Other considerations***

### **Alternative biochemistries**

While most investigations of extraterrestrial life start with the assumption that advanced life-forms must have similar requirements for life as on Earth, the hypothesis of other types of biochemistry suggests the possibility of lifeforms evolving around a different metabolic mechanism. In *Evolving the Alien*, biologist Jack Cohen and mathematician Ian Stewart argue astrobiology, based on the Rare Earth hypothesis, is restrictive and unimaginative. They suggest that Earth-like planets may be very rare, but non-carbon-based complex life could possibly emerge in other environments. The most frequently mentioned alternative to carbon is silicon-based life, while ammonia is sometimes suggested as an alternative solvent to water.

More speculative ideas have focused on bodies altogether different than Earth-like planets. Astronomer Frank Drake, a well-known proponent of the search for extraterrestrial life, imagined life on a neutron star: submicroscopic "nuclear molecules" combining to form creatures with a life cycle millions of times quicker than Earth life. Called "imaginative and tongue-in-cheek," the idea gave rise to science fiction depictions. Carl Sagan, another optimist with regards to extraterrestrial life, considered the possibility of organisms that are always airborne within the high atmosphere of Jupiter in a 1976 paper. Cohen and Stewart also envisioned life in both a solar environment and in the atmosphere of a gas giant.

### **"Good Jupiters"**

"Good Jupiters" are gas giant planets, like the solar system's Jupiter, that orbit their stars in circular orbits far enough away from the habitable zone to not disturb it but close enough to "protect" terrestrial planets in closer orbit in two critical ways. First, they help to stabilize the orbits, and thereby the climates, of the inner planets. Second, they keep the inner solar system relatively free of comets and asteroids that could cause devastating impacts. Jupiter orbits the Sun at about five times the distance between the Earth and the Sun. This is the rough distance we should expect to find good Jupiters elsewhere. Jupiter's "caretaker" role was dramatically illustrated in 1994 when Comet Shoemaker-Levy 9 impacted the giant; had Jovian gravity not captured the comet, it may well have entered the inner solar system.

Early in the Solar System's history, Jupiter played a somewhat contrary role: it increased the eccentricity of asteroid belt orbits and enabled many to cross Earth's orbit and supply the planet with important volatiles. Before Earth reached half its present mass, icy bodies from the Jupiter–Saturn region and small bodies from the primordial asteroid belt supplied water to the Earth due to the gravitational scattering of Jupiter and, to a lesser extent, Saturn. Thus, while the gas giants are now helpful protectors, they were once suppliers of critical habitability material.

In contrast, Jupiter-sized bodies that orbit too close to the habitable zone but not in it (as in 47 Ursae Majoris), or have a highly elliptical orbit that crosses the habitable zone (like 16 Cygni B) make it very difficult for an Earthlike planet to exist in the system.

### **Life's impact on habitability**

A supplement to the factors that support life's emergence is the notion that life itself, once formed, becomes a habitability factor in its own right. An important Earth example was the production of oxygen by ancient cyanobacteria, and eventually photosynthesizing plants, leading to a radical change in the composition of Earth's atmosphere. This oxygen would prove fundamental to the respiration of later animal species.

This interaction between life and subsequent habitability has been explored in various ways. The Gaia hypothesis, a class of scientific models of the geo-biosphere pioneered by Sir James Lovelock in 1975, argues that life as a whole fosters and maintains suitable conditions for itself by helping to create a planetary environment suitable for its continuity; at its most dramatic, Gaia suggests that planetary systems behave similarly to a kind of organism. The most successful life forms change the composition of the air, water, and soil in ways that make their continued existence more certain—a controversial extension of the accepted laws of ecology.

Similarly, David Grinspoon has suggested a "Living Worlds hypothesis" in which our understanding of what constitutes habitability cannot be separated from life already extant on a planet. Planets that are geologically and meteorologically alive are much more likely to be biologically alive as well and "a planet and its life will co-evolve."

In their 2004 book *The Privileged Planet*, astronomer Guillermo Gonzalez and philosopher Jay Richards explore the possible link between the habitability of a planet and its suitability for observing the rest of the universe. The book was criticized as an example of intelligent design and for its lack of scientific credibility.

## Chapter-6

# Cloud Reflectivity Modification

**Cloud reflectivity enhancement** is also known as 'marine cloud brightening' or 'cloud whitening' on low cloud. An opposite scheme exists to reduce the reflectivity of higher, colder cirrus clouds. It is a geoengineering technique that works by solar radiation management. By modifying the reflectivity of clouds, the albedo of the Earth is altered. The intention is that this technique, in combination with greenhouse gas emissions reduction (and possibly other geoengineering techniques) will be sufficient to control global warming. Compared to other climate modification strategies, this technique is relatively simple and benign, being based as it is on natural processes of 'ocean spray'. It can therefore be deployed quickly for further research, and can then be rolled out on an effective scale relatively cheaply after that. The effect is expected to be fully reversible, as the cloud condensation nuclei particles precipitate naturally. However, like any planetary-scale project dealing with the complex climate system, there is a non-trivial risk of unintended consequences.

### ***Basic principles***

Low level stratocumulus clouds cover approximately one-third of the oceans surface. These clouds possess Albedo levels of 0.3-0.7. The levels of albedo present in the low-level marine stratocumulus clouds create a significant global cooling effect. Theoretically, by increasing the albedo of the clouds, via spraying sea water(NaCl) droplets approximately 1  $\mu\text{m}$  in size, the cooling effects of the clouds are increased and potentially their longevity is enhanced. By creating cloud condensation nuclei, geoengineers can change the albedo of clouds to make them appear whiter. This can be done using a variety of chemicals and techniques, with seawater sprays from ships being a simple example. Broadly speaking, the marine environment has a deficit of cloud condensation nuclei due to lower levels of dust and pollution at sea, so this technique is more effective over the ocean than over land.

## ***Models***

### **HadGAM1 general circulation model**

A study by Jones, Latham, and Smith using the Hadley Center's General Circulation Model, suggests that warming due to a x2 increase in CO<sub>2</sub> could potentially be compensated for by a doubling of the droplet concentration number in low-level marine stratocumulus clouds, accounting for anthropogenic aerosol production, in three regions—off the coasts of the Americas and West Africa. The three regions combined cover approximately 3% of the Earth's surface.

### **Model of marine stratocumulus clouds developed by Bower, Jones and Choulaton**

Bower, Jones and Choulaton created a model to analyze the effectiveness of albedo modification on clouds. A 2006 study simplified the model. Their model illustrates the practicality of the technique. It demonstrates droplet size is not of that much importance, that location of clouds is of limited importance, and that significant cooling can be achieved with a level of .03.

## ***Proposed schemes***

### **Seawater spray**

Various schemes have been suggested, such as that proposed by John Latham and Stephen Salter, which works by spraying seawater in the atmosphere to increase the reflectiveness of clouds. The extra condensation nuclei created by the spray will change the size distribution of the drops in existing clouds to make them whiter. The sprayers would use a fleet of around 1500 unmanned Rotor ships known as Flettner vessels to spray mist created from seawater into the air to thicken clouds and thus reflect more radiation from the Earth. The whitening is achieved as a result of the Twomey effect. In order to significantly cool the earth, the vessels have to spray sea water droplets at a rate of 50 cubic meter per second over a large portion of the Earth's ocean surface.

This technique can give  $>3.7 \text{ W/m}^2$  of globally-averaged negative forcing, which is sufficient to reverse the warming effect of a doubling of CO<sub>2</sub>.

### ***Ultrasonic Excitation of a Liquid Using a Piezo-Electric Transducer***

This technique works by creating faraday waves at a free surface. If the waves are steep enough the droplets of sea water will be thrown from the crests and particles can enter into the clouds within a predictable area. However, a significant amount of energy is required.

## ***Electrostatic Atomisation of Seawater Drops***

This technique utilizes mobile spray platforms which move to adjust to changing weather conditions. A proposed idea is to use unmanned ships that shoot sea spray into the air.

### **Cloud Seeding Yachts**

Stephen Salter developed an unmanned yacht that uses Flettner rotors for propulsion. The rotors are vertical cylinders located on the deck of the yacht. The spray the tiny water droplets into the low level clouds to enhance their reflectivity. The power for the rotors and the ship is generated from underwater turbines. Approximately 1,500 of these ships would be required for the scheme to effectively cool the planet. The Royal Society states that "approximately 1500 spray vessels would be required to produce a negative forcing of  $-3.7 \text{ W m}^{-2}$ . Each vessel would require approximately 150 kW of electrical energy to atomize and disseminate seawater at the necessary continuous rate (as well as to support navigation, controls, communications, etc.), so that the global power requirement is approximately  $2.3 \times 10^8$  Watts." This technique requires far less energy compared to many other geoengineering techniques.

## **Ocean Sulfur Cycle Enhancement**

Enhancing the natural sulfur cycle in the Southern Ocean by fertilizing a small portion with iron in order to enhance dimethyl sulfide production and cloud reflectivity. The goal is to slow Antarctic ice from melting and raising sea level. Such techniques also tend to sequester carbon, but in this specific project the enhancement of cloud albedo was both the desired outcome and measured result.

This technique can give only  $0.016 \text{ W/m}^2$  of globally-averaged negative forcing, which is practically insignificant as a contribution to reducing global warming. However, as it is a regionally-acting technique its effects are concentrated in an influence on the climate of Antarctica.

## ***Advantages and Disadvantages***

### **Advantages**

- The techniques use natural and reusable resources i.e sea water and wind
- You can monitor cloud albedo levels via satellite and adjust the sea spraying mechanisms to fit the data.
- Albedo enhancement is considerably cheaper than many other geoengineering techniques.
- It utilizes already existing technologies to send sea water droplets into low level oceanic clouds.
- The location of the albedo enhancement of clouds can be controlled and localized. This could prevent ecological problems.

- Cooling can happen in only the places in which it is required.

## **Disadvantages**

- Most of the information on albedo enhancement on clouds is from models and computer simulations. The actual results from spraying sea water into low level clouds may differ from the predicted effect.
- Currently the two most commonly proposed plans for sea water dispersal are airplanes and turbine powered ships. The use of airplanes will be time consuming, labor intensive, and result in a large amount of carbon emissions. Turbine powered un-manned ships are the most ecologically friendly, but their capacity to fulfill the role is still not known.
- The technique is strongly dependent on wind patterns.
- The meteorological affects cannot be known until real world testing is conducted.
- If CO<sub>2</sub> increases beyond the predicted rate then albedo enhancement of clouds may not be strong enough to cool the Earth.
- The effect of aerosols and its impact on albedo enhancement of clouds has not been significantly researched.

## **Further research**

- The amount of water droplets that enter clouds and form additional droplets is not currently known and is affected largely by meteorological factors. Research must be done to assess what percentage of particles will be successful and what the effect of the weather is.
- Charging sea water particles to utilize the Earth's electric field may be beneficial.
- Climatological and meteorological ramifications must be studied as the technique will alter rainfall, temperature, static stability, and ocean currents.
- The effect of aerosols on low level clouds must be better understood. The aerosols may negatively impact efforts to enhance the albedo of clouds.

## **Reducing cirrus reflectivity**

Cirrus clouds are capable of modification to reduce their reflectivity (opposite to the low-cloud scheme), using seeding mechanisms distributed by airliners. The climatic effects of this modification operate in the opposite direction to that of the lower, warmer clouds modified in the cloud brightening scheme. This authors calculate that this scheme is sufficient to reverse the warming caused by a doubling of CO<sub>2</sub>.

## Chapter-7

# Iron Fertilization



An oceanic phytoplankton bloom in the South Atlantic Ocean, off the coast of Argentina covering an area about 300 miles by 50 miles

**Iron fertilization** is the intentional introduction of iron to the upper ocean to stimulate a phytoplankton bloom. This is intended to enhance biological productivity, which can benefit the marine food chain and remove carbon dioxide from the atmosphere. Iron is a trace element necessary for photosynthesis in all plants. It is highly insoluble in sea water

and is often the limiting nutrient for phytoplankton growth. Large phytoplankton blooms can be created by supplying iron to iron-deficient ocean waters. A number of ocean labs, scientists and businesses are exploring fertilization as a means to sequester atmospheric carbon dioxide in the deep ocean, and to increase marine biological productivity which is likely in decline as a result of climate change. Since 1993, thirteen international research teams have completed ocean trials demonstrating that phytoplankton blooms can be stimulated by iron addition. However, controversy remains over the effectiveness of atmospheric CO<sub>2</sub> sequestration and ecological effects. The most recent open ocean trial of ocean iron fertilization, dubbed LOHAFEX, was conducted from January to March 2009 in the South Atlantic.

Fertilization also occurs naturally when upwellings bring nutrient-rich water to the surface, as occurs when ocean currents meet an ocean bank or a sea mount. This form of fertilization produces the world's largest marine habitats. Fertilization can also occur when weather carries wind blown dust long distances over the ocean, or iron-rich minerals are carried into the ocean by glaciers, rivers and icebergs.

## ***History***

Consideration of iron's importance to phytoplankton growth and photosynthesis dates back to the 1930s when English biologist Joseph Hart speculated that the ocean's great "desolate zones" (areas apparently rich in nutrients, but lacking in plankton activity or other sea life) might simply be iron deficient. Little further scientific discussion of this issue was recorded until the 1980s, when oceanographer John Martin renewed controversy on the topic with his marine water nutrient analyses. His studies indicated it was indeed a scarcity of iron micronutrients that was limiting phytoplankton growth and overall productivity in these "desolate" regions, which came to be called "High Nutrient, Low Chlorophyll" (HNLC) zones.

Martin's famous 1991 quip at Woods Hole Oceanographic Institution, "Give me a half a tanker of iron and I will give you another ice age", drove a decade of research whose findings suggested that iron deficiency was not merely impacting ocean ecosystems, it also offered a key to mitigating climate change as well.

Perhaps the most dramatic support for Martin's hypothesis was seen in the aftermath of the 1991 eruption of Mount Pinatubo in the Philippines. Environmental scientist Andrew Watson analyzed global data from that eruption and calculated that it deposited approximately 40,000 tons of iron dust into the oceans worldwide. This single fertilization event generated an easily observed global decline in atmospheric CO<sub>2</sub> and a parallel pulsed increase in oxygen levels.

## ***Experiments***

Martin hypothesized that increasing phytoplankton photosynthesis could slow or even reverse global warming by sequestering enormous volumes of CO<sub>2</sub> in the sea. He died shortly thereafter during preparations for Ironex I, a proof of concept research voyage,

which was successfully carried out near the Galapagos Islands in 1993 by his colleagues at Moss Landing Marine Laboratories. Since then 9 international ocean studies have examined the fertilization effects of iron:

- Ironex II, 1995
- SOIREE (Southern Ocean Iron Release Experiment), 1999
- EisenEx (Iron Experiment), 2000
- SEEDS (Subarctic Pacific Iron Experiment for Ecosystem Dynamics Study), 2001
- SOFeX (Southern Ocean Iron Experiments - North & South), 2002
- SERIES (Subarctic Ecosystem Response to Iron Enrichment Study), 2002
- SEEDS-II, 2004
- EIFEX (European Iron Fertilization Experiment), 2004
- CROZEX (CROZet natural iron bloom and Export experiment), 2005
- LOHAFEX (Indian and German Iron Fertilization Experiment), 2009

Despite widespread opposition to LOHAFEX, on 26 January 2009 the German Federal Ministry of Education and Research (BMBF) gave clearance for this fertilization experiment to commence. The experiment was carried out in waters low in silicic acid which is likely to affect the efficacy of carbon sequestration. A 900 square kilometres (350 sq mi) portion of the southwest Atlantic Ocean was fertilized with iron sulfate. A large phytoplankton bloom was triggered, however this bloom did not contain diatoms because the fertilized location was already depleted in silicic acid, an essential nutrient for diatom growth. In the absence of diatoms, a relatively small amount of carbon was sequestered, because other phytoplankton are vulnerable to predation by zooplankton and do not sink rapidly upon death. These poor sequestration results have caused some, including members of the LOHAFEX research team, to suggest that ocean iron fertilization is not an effective carbon mitigation strategy *in general*, however prior ocean fertilization experiments in high silica locations have observed much higher carbon sequestration rates because of diatom growth. LOHAFEX has just confirmed that the carbon sequestration potential depends strongly upon careful choice of location.

The maximum possible result from iron fertilization, assuming the most favourable conditions and disregarding practical considerations, is  $0.29\text{W/m}^2$  of globally-averaged negative forcing, which is almost sufficient to reverse the warming effect of about 1/6 of current levels of anthropogenic  $\text{CO}_2$  emissions. It is notable, however, that  $\text{CO}_2$  levels will have risen by the time this could be achieved.

## **Science**

### **The role of iron**

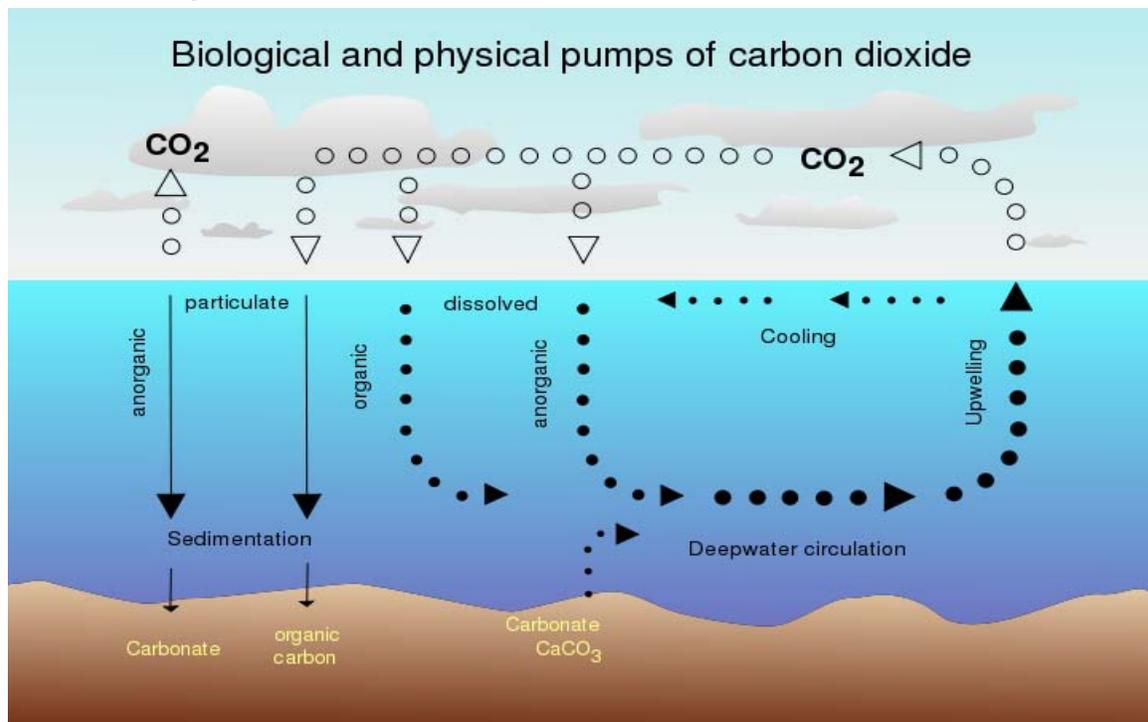
About 70% of the world's surface is covered in oceans, and the upper part of these (where light can penetrate) is inhabited by algae. In some oceans, the growth and reproduction of these algae is limited by the amount of iron in the seawater. Iron is a vital micronutrient for phytoplankton growth and photosynthesis that has historically been delivered to the

pelagic sea by dust storms from arid lands. This Aeolian dust contains 3–5% iron and its deposition has fallen nearly 25% in recent decades.

The Redfield ratio describes the relative atomic concentrations of critical nutrients in plankton biomass and is conventionally written "106 C: 16 N: 1 P." This expresses the fact that one atom of phosphorus and 16 of nitrogen are required to "fix" 106 carbon atoms (or 106 molecules of  $\text{CO}_2$ ). Recent research has expanded this constant to "106 C: 16 N: 1 P: .001 Fe" signifying that in iron deficient conditions each atom of iron can fix 106,000 atoms of carbon, or on a mass basis, each kilogram of iron can fix 83,000 kg of carbon dioxide. The 2004 EIFEX experiment reported a carbon dioxide to iron export ratio of nearly 3000 to 1. The atomic ratio would be approximately: "3000 C: 58,000 N: 3,600 P: 1 Fe".

Therefore small amounts of iron (measured by mass parts per trillion) in "desolate" HNLC zones can trigger large phytoplankton blooms. Recent marine trials suggest that one kilogram of fine iron particles may generate well over 100,000 kilograms of plankton biomass. The size of the iron particles is critical, however, and particles of 0.5–1 micrometer or less seem to be ideal both in terms of sink rate and bioavailability. Particles this small are not only easier for cyanobacteria and other phytoplankton to incorporate, the churning of surface waters keeps them in the euphotic or sunlit biologically active depths without sinking for long periods of time.

### Carbon sequestration



Air-sea exchange of  $\text{CO}_2$

Previous instances of biological carbon sequestration have triggered major climatic changes, such as the Azolla event. Plankton that generate calcium or silicon carbonate skeletons, such as diatoms, coccolithophores and foraminifera, account for most direct carbon sequestration. When these organisms die their carbonate skeletons sink relatively quickly and form a major component of the carbon-rich deep sea precipitation known as marine snow. Marine snow also includes fish fecal pellets and other organic detritus, and can be seen steadily falling thousands of meters below active plankton blooms.

Of the carbon-rich biomass generated by plankton blooms, half (or more) is generally consumed by grazing organisms (zooplankton, krill, small fish, etc.) but 20 to 30% sinks below 200 meters (656 ft) into the colder water strata below the thermocline. Much of this fixed carbon continues falling into the abyss, but a substantial percentage is redissolved and remineralized. At this depth, however, this carbon is now suspended in deep currents and effectively isolated from the atmosphere for centuries. (The surface to benthic cycling time for the ocean is approximately 4,000 years.)

## **Analysis and quantification**

Evaluation of the biological effects and verification of the amount of carbon actually sequestered by any particular bloom requires a variety of measurements, including a combination of ship-borne and remote sampling, submarine filtration traps, tracking buoy spectroscopy and satellite telemetry. Unpredictable ocean currents have been known to remove experimental iron patches from the pelagic zone, invalidating the experiment.

The potential of iron fertilization as a geoengineering technique to tackle global warming is illustrated by the following figures. If phytoplankton converted all the nitrate and phosphate present in the surface mixed layer across the entire Antarctic circumpolar current into organic carbon, the resulting carbon dioxide deficit could be compensated by uptake from the atmosphere amounting to about 0.8 to 1.4 gigatonnes of carbon per year. This quantity is comparable in magnitude to annual anthropogenic fossil fuels combustion of approximately 6 gigatonnes. It should be noted that the Antarctic circumpolar current region is only one of several in which iron fertilization could be conducted—the Galapagos islands area being another potentially suitable location.

## **Dimethyl sulfide and clouds**

Some species of plankton produce dimethyl sulfide (DMS), a portion of which enters the atmosphere where it is oxidized by hydroxyl radicals (OH), atomic chlorine (Cl) and bromine monoxide (BrO) to form sulfate particles and ultimately clouds. This may increase the albedo of the planet and so cause cooling. This is the basic tenet of the Gaia hypothesis and was presented in James Lovelock's first paper published on this topic.

During the Southern Ocean Iron Enrichment Experiments (SOFeX), DMS concentrations increased by a factor of four inside the fertilized patch. Widescale iron fertilization of the Southern Ocean could lead to significant sulfur-triggered cooling in addition to that due

to the increased CO<sub>2</sub> uptake and that due to the ocean's albedo increase, however the amount of cooling by this particular effect is very uncertain.

### ***Financial opportunities***

Since the advent of the Kyoto Protocol, several countries and the European Union have established carbon offset markets which trade certified emission reduction credits (CERs) and other types of carbon credit instruments internationally. In 2007 CERs sell for approximately €15–20/ton CO<sub>2</sub>e and European analysts project these prices will nearly double by 2012. Iron fertilization is relatively inexpensive compared to scrubbing, direct injection and other industrial approaches, and can theoretically sequester for less than €5/ton CO<sub>2</sub>, creating a substantial return. In August, 2010, Russia established a minimum price of €10/ton for offsets to reduce uncertainty for offset providers. Scientists have reported a minimum 6–12% decline in global plankton production since 1980. A full-scale international plankton restoration program could regenerate approximately 3–5 billion tons of sequestration capacity worth €50–100 billion in carbon offset value. Given this potential return on investment, carbon traders and offset customers are watching the progress of this technology with interest.

### ***Multilateral reaction***

The parties to the London Dumping Convention (Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972) adopted a non-binding resolution in 2008 on fertilization (labeled LC-LP.1(2008)). The resolution states that ocean fertilization activities, other than legitimate scientific research, "should be considered as contrary to the aims of the Convention and Protocol and do not currently qualify for any exemption from the definition of dumping".

An Assessment Framework for Scientific Research Involving Ocean Fertilization, regulating the dumping of wastes at sea (labeled LC-LP.2(2010)) was adopted by the Contracting Parties to the Convention in October 2010 (LC 32/LP 5).

### ***Sequestration definitions***

Carbon is not considered "sequestered" unless it settles to the ocean floor where it remains for eons. Most of the carbon that sinks beneath plankton blooms is dissolved and remineralized well above the seafloor and will eventually (days to centuries) return to the atmosphere, negating the original effect.

Advocates argue that modern climate scientists and Kyoto Protocol policy makers define sequestration in much shorter time frames. For example, they recognize trees and grasslands as important carbon sinks. Forest biomass only sequesters carbon for decades, but carbon that sinks below the marine thermocline (100–200 meters) is effectively removed from the atmosphere for hundreds of years, whether it is remineralized or not. Since deep ocean currents take so long to resurface, their carbon content is effectively sequestered by the criterion in use today.

## **Debate**

While many advocates of ocean iron fertilization see it as modern society's last best hope to slow global warming, some academics, deep greens and proponents of competing technologies cite a variety of concerns.

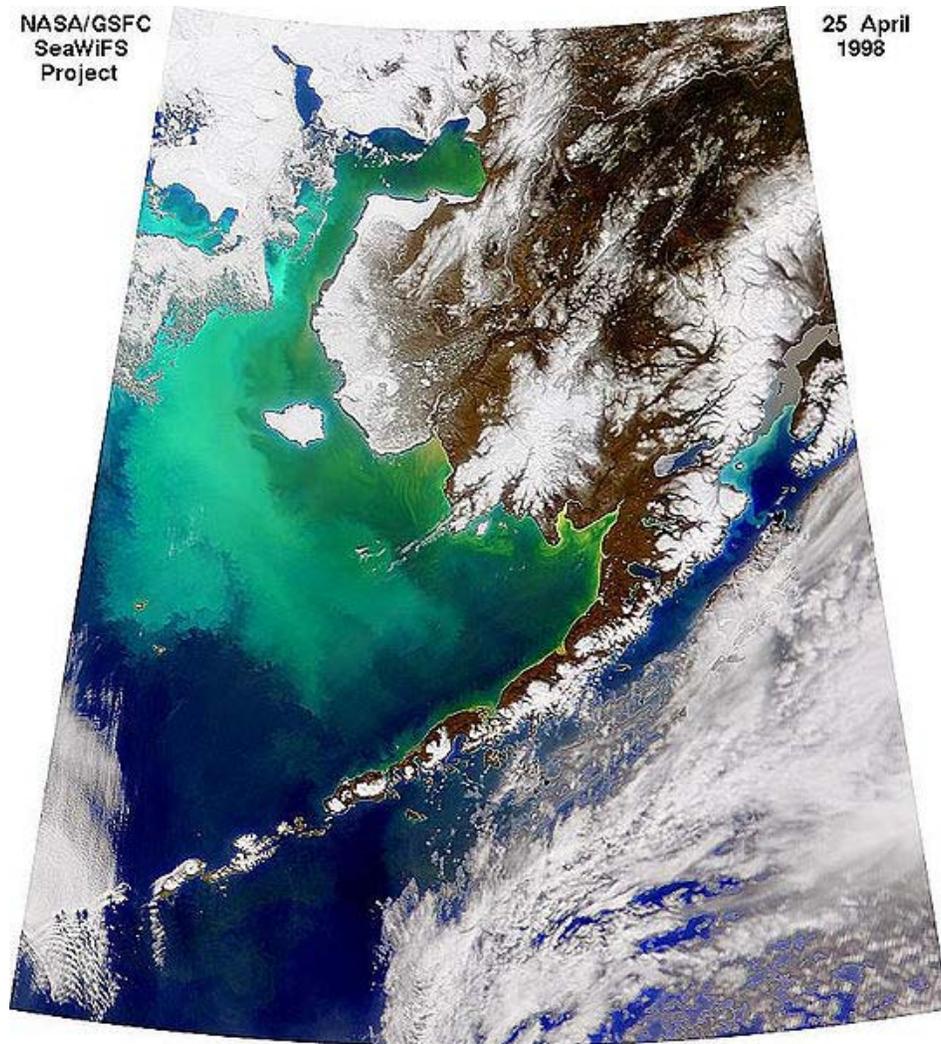
### **Precautionary principle**

The *precautionary principle* (PP) states that if an action or policy has a suspected risk of causing harm, in the absence of scientific consensus, the burden of proof that it is not harmful falls on those who would take the action. The side effects of large-scale iron fertilization are not yet known. Creating phytoplankton blooms in naturally iron-poor areas of the ocean is like watering the desert: in effect it changes one type of ecosystem into another. Such large and rapid conversions have no precedent.

The argument can be applied in reverse, by considering emissions to be the action and remediation an attempt to partially offset the damage.

### **20th century phytoplankton decline**

While advocates argue that iron addition would help to reverse a supposed decline in phytoplankton, this decline may not be real. One study reported a decline in ocean productivity comparing the 1979–1986 and 1997–2000 periods, but two others found *increases* in phytoplankton.



Satellite image of a large, natural, coccolithophore bloom in the Bering Sea in 1998.

### **Comparison to prior phytoplankton cycles**

Fertilization advocates respond that similar algal blooms have occurred naturally for millions of years with no observed ill effects. The Azolla event occurred around 49 million years ago and accomplished what fertilization is intended to achieve (but on a larger scale).

### **Sequestration efficiency**

Fertilization may sequester too little carbon per bloom, supporting the food chain rather than raining on the ocean floor, and thus require too many seeding voyages to be practical. A 2009 Indo-German team of scientists examined the potential of the southwestern Atlantic to sequester significant amounts of carbon dioxide, but found few positive results.

The counter-argument to this is that the low sequestration estimates that emerged from some ocean trials are largely due to these factors:

1. **Data:** none of the ocean trials had enough boat time to monitor their blooms for more than 27 days, confining their measurements to that period. Blooms generally last 60–90 days with the heaviest "precipitation" occurring during the last two months.
2. **Scale:** most trials used less than 1,000 kilograms (2,205 lb) of iron and thus created small blooms that were quickly devoured by opportunistic zooplankton, krill, and fish that swarmed into the seeded region.

Some ocean trials reported positive results. IronEx II reported conversion of 1,000 kilograms (2,205 lb) to carbonaceous biomass equivalent to one hundred full-grown redwoods within two weeks. Eifex recorded fixation ratios of nearly 300,000 to 1.

Current estimates of the amount of iron required to restore all the lost plankton and sequester 3 gigatons/year of CO<sub>2</sub> range widely, from approximately 2 hundred thousand tons/year to over 4 million tons/year. The latter scenario involves 16 supertanker loads of iron and a projected cost of approximately €20 billion (\$27 billion).

## Ecological issues

### Algal blooms



A "red tide" off the coast of La Jolla, San Diego, California.

Critics are concerned that fertilization will create *harmful algal blooms* (HAB). The species that respond most strongly to fertilization vary by location and other factors and could possibly include species that cause red tides and other toxic phenomena. These factors affect only near-shore waters, although they show that increased phytoplankton populations are not universally benign.

Most species of phytoplankton are harmless or beneficial, given that they constitute the base of the marine food chain. Fertilization increases phytoplankton only in the deep oceans (far from shore) where iron deficiency is the problem. Most coastal waters are replete with iron and adding more has no useful effect.

A 2010 study of iron fertilization in an oceanic high-nitrate, low-chlorophyll environment, however, found that fertilized *Pseudo-nitzschia* diatom spp., which are generally nontoxic in the open ocean, began producing toxic levels of domoic acid. Even short-lived blooms containing such toxins could have detrimental effects on marine food webs.

## **Deep water oxygen levels**

When organic bloom detritus sinks into the abyss, a significant fraction will be devoured by bacteria, other microorganisms and deep sea animals which also consume oxygen. A large enough bloom could render certain regions of the sea deep beneath it anoxic and threaten other benthic species.

The largest plankton replenishment projects under consideration are less than 10% the size of most natural wind-fed blooms. In the wake of major dust storms, natural blooms have been studied since the beginning of the 20th century and no such deep water dieoffs have been reported.

## **Ecosystem effects**

Depending upon the composition and timing of delivery, iron infusions could preferentially favor certain species and alter surface ecosystems to unknown effect. Population explosions of jellyfish, disturbance of the food chain impacting whale populations or fisheries are potential risks.

A 2010 study shows that iron enrichment stimulates toxic diatom production in high-nitrate, low-chlorophyll areas, which, the authors argue, raises "serious concerns over the net benefit and sustainability of large-scale iron fertilizations".

However, CO<sub>2</sub>-induced surface water heating and rising carbonic acidity are *already* shifting population distributions for phytoplankton, zooplankton and many other creatures. Optimal fertilization could potentially help restore lost/threatened ecosystem services.

## **Conclusion and further research**

Critics and advocates generally agree that most questions on the impact, safety and efficacy of ocean iron fertilization can only be answered by much larger studies.

A statement published in *Science* in 2008 maintained that it would be

premature to sell carbon offsets from the first generation of commercial-scale OIF experiments unless there is better demonstration that OIF effectively removes CO<sub>2</sub>, retains that carbon in the ocean for a quantifiable amount of time, and has acceptable and predictable environmental impacts.

One pilot project planned by Planktos, a U.S. company, was cancelled in 2008 for lack of funding. The company blamed environmental organisations for the failure.

## Chapter-8

# Terraforming of Mars



Artist's conception of the process of terraforming Mars.

The **terraforming of Mars** is the hypothetical process by which the climate, surface, and known properties of Mars would be deliberately changed with the goal of making it

habitable by humans and other terrestrial life, thus providing the possibility of safe and sustainable colonization of large areas of the planet. The concept is reliant on the assumption that the environment of a planet can be altered through man-made means; the feasibility of creating an unconstrained planetary biosphere is undetermined. There are several proposed methods, some of which present prohibitive economic and natural resource costs, and others which may be currently technologically achievable.

## ***Reasons for terraforming***

In the future, population growth and demand for resources may create pressure for humans to colonize new habitats such as Mars, the Moon, and nearby planets, as well as harvest the Solar System's energy and material resources. Terraforming Mars would hypothetically make Mars habitable to humans.

Terraforming Mars may allow for preservation of Earth's species in the event of a catastrophic extinction event, such as the meteor commonly believed to have killed off the dinosaurs 65 million years ago. Additionally, in approximately 7.6 billion years the Sun will enter a red giant phase, as the hydrogen fuel in the core is completely consumed causing the Sun's core to contract and the outer layers to expand. At this point, the Sun's upper atmosphere will extend as far as 1.2 AU, out past the present orbit of the Earth. This expansion will likely destabilize the orbits of the inner planets, causing them to spiral in towards the sun and be destroyed. The Sun will lose a significant fraction of its mass in the process of becoming a red giant, and this may cause a widening of the orbits of the other planets. Earth could technically achieve a widening of its orbit and could potentially maintain a sufficiently high angular velocity to keep it from being engulfed. In order to do so, its orbit would need to increase to between 1.3 AU and 1.7 AU.

It is speculated that Earth will be out of its habitable zone before the Sun enters its Red Giant phase. Astronomers estimate that the Sun will be 33% more luminous in three billion years. The warming Sun and increased solar radiation will cause the Earth's oceans to evaporate, and the Earth to eventually become molten again. The habitable zone would move farther out from the Sun, giving potential Mars colonists some thousands of additional years to develop further space technology to settle elsewhere in the Solar System.

## ***Background***

Mars already consists of many soil minerals that could theoretically be used for terraforming. Large amounts of water ice exist below the Martian surface, as well as on the surface at the poles, where it is mixed with dry ice, frozen CO<sub>2</sub>. It has been found that significant amounts of water are stored in the south pole of Mars, and if all of this ice suddenly melted, it would form a planetwide ocean 11 meters deep. Frozen carbon dioxide (CO<sub>2</sub>) at the poles sublimates into the atmosphere during the Martian summer, and small amounts of water residue are left behind, which fast winds sweep off the poles at speeds approaching 250 mph (400 km/h). This seasonal occurrence transports large

amounts of dust and water vapor into the atmosphere, giving potential for Earth-like cirrus clouds.

Most of the elemental oxygen in the Martian atmosphere is present as carbon dioxide (CO<sub>2</sub>), the main atmospheric component; molecular oxygen (O<sub>2</sub>) only exists in trace amounts. Large amounts of elemental oxygen can be also found in metal-oxides on the Martian surface, and in the soil, in the form of per-nitrates. An analysis of soil samples taken by the Phoenix lander indicated the presence of perchlorate, which has been used to liberate oxygen in chemical oxygen generators. Electrolysis could be employed to separate water on the planet into oxygen and hydrogen if sufficient liquid water and electricity were available.

It has been suggested that Mars once had an environment relatively similar to that of Earth during an earlier stage in its development. While water once appears to have existed on the Martian surface, it now only appears to exist at the poles and just below the planetary surface as permafrost. Gravity of Mars today indicates that lighter gases in the upper atmosphere could have contributed to the thinning of the atmosphere, with the excess atoms escaping into space; also the evident lack of plate tectonics on Mars would in theory slow the recycling of gases from being locked in sediments back into the atmosphere, and the high amounts of Solar Wind on Mars are other plausible contributing factors. The lack of a magnetic field and geologic activity may both be a result of Mars' smaller size, which allows its interior to cool more quickly than Earth's, though the details of such a process are still not well understood.

## ***Changes required***

### **Comparison of dry atmosphere**

	<b>Mars</b>	<b>Earth</b>
<b>Pressure</b>	<b>0.6 kPa (0.087 psi)</b>	<b>101.3 kPa (14.69 psi)</b>
<b>Carbon dioxide (CO<sub>2</sub>)</b>	<b>95.32%</b>	<b>0.04%</b>
<b>Nitrogen (N<sub>2</sub>)</b>	<b>2.70%</b>	<b>78.08%</b>
<b>Argon (Ar)</b>	<b>1.60%</b>	<b>0.93%</b>
<b>Oxygen (O<sub>2</sub>)</b>	<b>0.13%</b>	<b>20.94%</b>

Terraforming Mars would entail three major interlaced changes: building up the atmosphere, keeping it warm, and keeping the atmosphere from being lost into outer space. The atmosphere of Mars is relatively thin and thus has a very low surface pressure of 0.6 kilopascals (0.087 psi); compared to Earth with 101.3 kilopascals (14.69 psi) at sea level and 0.86 kilopascals (0.125 psi) at an altitude of 32 kilometres (20 mi). The atmosphere on Mars consists of 95% carbon dioxide (CO<sub>2</sub>), 3% nitrogen, 1.6% argon, and contains only traces of oxygen, water, and methane. Since its atmosphere consists mainly of CO<sub>2</sub>, a known greenhouse gas, once the planet begins to heat, more CO<sub>2</sub> enters the atmosphere from the frozen reserves on the poles, adding to the greenhouse effect. This means that the two processes of building the atmosphere and heating it would augment one another, favoring terraforming. However, on a large scale, controlled

application of certain techniques (*explained below*) over enough time to achieve sustainable changes would be required to make this hypothesis a reality.

### **Building the atmosphere, water content**

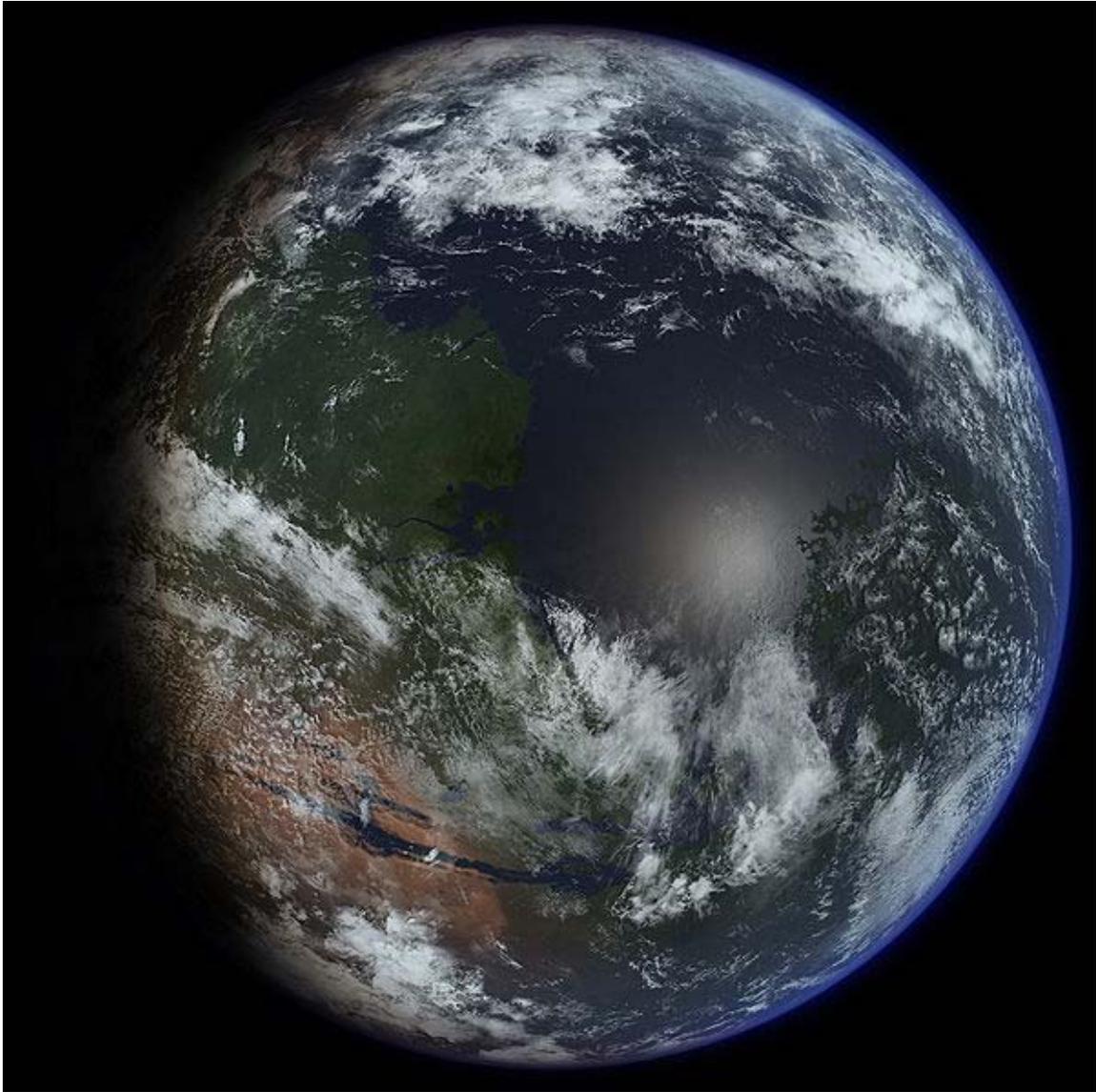


Artist's conception of a terraformed Mars centered on the Tharsis region.

An important step in building the martian atmosphere would be the importation of water, that can be obtained, for example, from ice asteroids or from ice moons of Jupiter or Saturn, beyond the water ice already present at the Martian north pole.

## Sources of water

A substantial, nearby source of water is the dwarf planet Ceres, which, according to various studies accounts for 25% to 33% of the mass of the Asteroid Belt. Ceres' mass is approximately  $9.43 \times 10^{20}$  kg. Estimates of how much of Ceres is water varies widely but 20% is a typical estimate and it is thought that much of the water forms the outer or near-surface level. The mass of Ceres' water equals approximately  $1.9 \times 10^{20}$  kg using the previous estimates. The total mass of Mars is approximately  $6.42 \times 10^{23}$  kg. Therefore a very rough estimate is that the amount of water on Ceres equals approximately 0.03 % of the total mass of Mars. Transporting a significant portion of this water, or water from any of the icy moons, could prove difficult. Any attempt to perturb the orbit of Ceres in order to add it whole to Mars (similar to the strategy of using a gravitational tractor for asteroid deflection,) must account for any resultant perturbation of the martian orbit and account for prolonged geological tumult, such as reestablishment of hydrostatic equilibrium, that could result from impact.



Artist's conception of a terraformed Mars. This portrayal is approximately centered on the prime meridian and 30° North latitude, and a hypothesized ocean with a sea level at approximately two kilometers below average surface elevation. The ocean submerges what are now Vastitas Borealis, Acidalia Planitia, Chryse Planitia, and Xanthe Terra; the visible landmasses are Tempe Terra at the left, Aonia Terra at the bottom, Terra Meridiani at the lower right, and Arabia Terra at the upper right. Rivers that feed the ocean at the lower right occupy what are now Valles Marineris and Ares Vallis, while the large lake at the lower right occupies what is now Aram Chaos.

### **Carbon dioxide sublimation**

There is presently enough carbon dioxide (CO<sub>2</sub>) as ice in the Martian south pole and absorbed by regolith (soil) around the planet that, if sublimated to gas by a climate warming of only a few degrees, would increase the atmospheric pressure to 300 millibars,

which is comparable to that at the peak of Mount Everest. While this would not be comfortably breathable by humans, it would eliminate the present need for pressure suits, melt the water ice at Mars' north pole (flooding the northern basin), and bring the year-round climate above freezing over approximately half of Mars' surface. This would enable the introduction of plant life, particularly plankton in the new northern sea, to start converting the atmospheric CO<sub>2</sub> into oxygen.

### **Ammonia importation**

Another, more intricate method, uses ammonia as a powerful greenhouse gas (as it is possible that large amounts of it exist in frozen form on asteroidal objects orbiting in the outer Solar System), it may be possible to move these (for example, by using very large nuclear bombs to blast them in the right direction) and send them into Mars' atmosphere. Since ammonia (NH<sub>3</sub>) is high in nitrogen it might also take care of the problem of needing a buffer gas in the atmosphere. Sustained smaller impacts will also contribute to increases in the temperature and mass of the atmosphere.

The need for a buffer gas is a challenge that will face any potential atmosphere builders. On Earth, nitrogen is the primary atmospheric component making up 77% of the atmosphere. Mars would require a similar buffer gas component although not necessarily as much. Still, obtaining significant quantities of nitrogen, argon or some other comparatively inert gas is difficult.

### **Hydrocarbons importation**

Another way would be to import methane or other hydrocarbons, which are common in Titan's atmosphere (and on its surface). The methane could be vented into the atmosphere where it would act to compound the greenhouse effect.

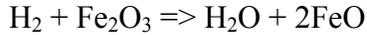
Methane (or other hydrocarbons) also can be helpful to produce a quick increase for the insufficient martian atmospheric pressure. These gases also can be used for production (at the next step of terraforming of Mars) of water and CO<sub>2</sub> for martian atmosphere, by reaction:



This reaction could probably be initiated by heat or by martian solar UV-irradiation. Large amounts of the resulting products (CO<sub>2</sub> and water) are necessary to initiate the photosynthetic processes.

### **Hydrogen importation**

Hydrogen importation could also be done for atmospheric and hydrospheric engineering. For example, hydrogen could react with iron(III) oxide from the martian soil, that would give water as a product:



Depending on the level of carbon dioxide in the atmosphere, importation and reaction of hydrogen would produce heat, water and graphite via the Bosch reaction. Alternatively, reacting hydrogen with the carbon dioxide atmosphere via the Sabatier reaction would yield methane and water.

## Using fluorine compounds

Since long-term climate stability would be required for sustaining a human population, the use of especially powerful fluorine-bearing greenhouse gases possibly including sulfur hexafluoride or halocarbons such as chlorofluorocarbons (or CFCs) and perfluorocarbons (or PFCs) has been suggested. These gases are the most cited candidates for artificial insertion into the Martian atmosphere because of their strong effect as a greenhouse gas. This can conceivably be done relatively cheaply by sending rockets with a payload of compressed CFCs on a collision course with Mars. When the rocket crashes onto the surface it releases its payload into the atmosphere. A steady barrage of these "CFC rockets" would need to be sustained for a little more than a decade while the planet changes chemically and becomes warmer.

In order to sublimate the south polar CO<sub>2</sub> glaciers, Mars would require the introduction of approximately 0.3 microbars of CFC (chloro-fluoro-carbons) into Mars' atmosphere. CFC are powerful greenhouse gases that are thousands of times more effective at warming than CO<sub>2</sub>. The 0.3 microbars needed would mass approximately 39 million metric tonnes, which is about three times the amount of CFC manufactured on Earth from 1972 to 1992 when CFC production was banned by international treaty. Mineralogical surveys of Mars have found significant amounts of the ores necessary to produce the amount of CFC gas required.

A proposal to mine fluorine-containing minerals as a source of CFCs and PFCs is supported by the belief that since the quantities present are expected to be at least as common on Mars as on Earth, this process could sustain the production of sufficient quantities of optimal greenhouse compounds (CF<sub>3</sub>SCF<sub>3</sub>, CF<sub>3</sub>OCF<sub>2</sub>OCF<sub>3</sub>, CF<sub>3</sub>SCF<sub>2</sub>SCF<sub>3</sub>, CF<sub>3</sub>OCF<sub>2</sub>NFCF<sub>3</sub>) to maintain Mars at 'comfortable' temperatures, as a method of maintaining an Earth-like atmosphere produced previously by some other means.

## Adding heat

Adding heat and conserving the heat present is a particularly important stage of this process, as heat from the Sun is the primary driver of planetary climate. As the planet would become warmer through various methods the CO<sub>2</sub> on the polar caps would sublime into the atmosphere and would further contribute to the warming effect. The tremendous air currents generated by the moving gasses would create large, sustained dust storms, which would heat (through absorbing solar radiation) the molecules in the atmosphere.

## **Orbiting mirrors**

Mirrors made of thin aluminized PET film could be placed in orbit around Mars to increase the total insolation it receives. This would direct the sunlight onto the surface and could increase the planet's surface temperature directly. The mirror could be positioned as a statite, using its effectiveness as a solar sail to orbit in a stationary position relative to Mars, near the poles, to sublimate the CO<sub>2</sub> ice sheet and contribute to the warming greenhouse effect.

## **Albedo**

Reducing the albedo of the Martian surface would also make more efficient use of incoming sunlight. This could be done by spreading dark dust from Mars' moons, Phobos and Deimos, which are among the blackest bodies in the Solar System; or by introducing dark extremophile microbial life forms such as lichens, algae and bacteria. The ground would then absorb more sunlight, warming the atmosphere.

If algae or other green life were established, it would also contribute a small amount of oxygen to the atmosphere, though not enough to allow humans to breathe.

## **Asteroid impact**

Another way to increase the temperature could be to direct small cosmic bodies (asteroids) onto the Martian surface; the impact energy would be released as heat and could vaporize Martian water ice to steam, which is also a greenhouse gas. Asteroids could also be chosen for their composition, such as Ammonia, which would then disperse into the atmosphere on impact, adding greenhouse gases to the atmosphere. Lightning may have built up nitrate beds in the soil over the life of the planet. Impacting asteroids on these nitrate beds would release additional nitrogen and oxygen into the atmosphere.

## ***Magnetic field and solar radiation***

Earth abounds with water because its ionosphere is permeated with a magnetic field. The hydrogen ions present in its ionosphere move very fast due to their small mass, but they cannot escape to outer space because their trajectories are deflected by the magnetic field. Venus has a dense atmosphere, but only traces of water vapor (20 ppm) because it has no magnetic field. The Martian atmosphere also loses water to space.

Earth's ozone layer provides additional protection. Ultraviolet light is blocked before it can dissociate water into hydrogen and oxygen. Since little water vapor rises above the troposphere and the ozone layer is in the upper stratosphere, little water is dissociated into hydrogen and oxygen.

It is believed that Mars would be uninhabitable to most life-forms due to high solar radiation levels. Because of the planet's lack of a magnetosphere, the Sun is thought to have thinned the Martian atmosphere to its current state; the solar wind adding a

significant amount of energy to the atmosphere's top layers which enables the atmospheric particles to reach escape velocity and leave Mars. Indeed, this effect has even been detected by Mars-orbiting probes. Another theory is that solar wind rips the atmosphere away from the planet as it becomes trapped in bubbles of magnetic fields called plasmoids.

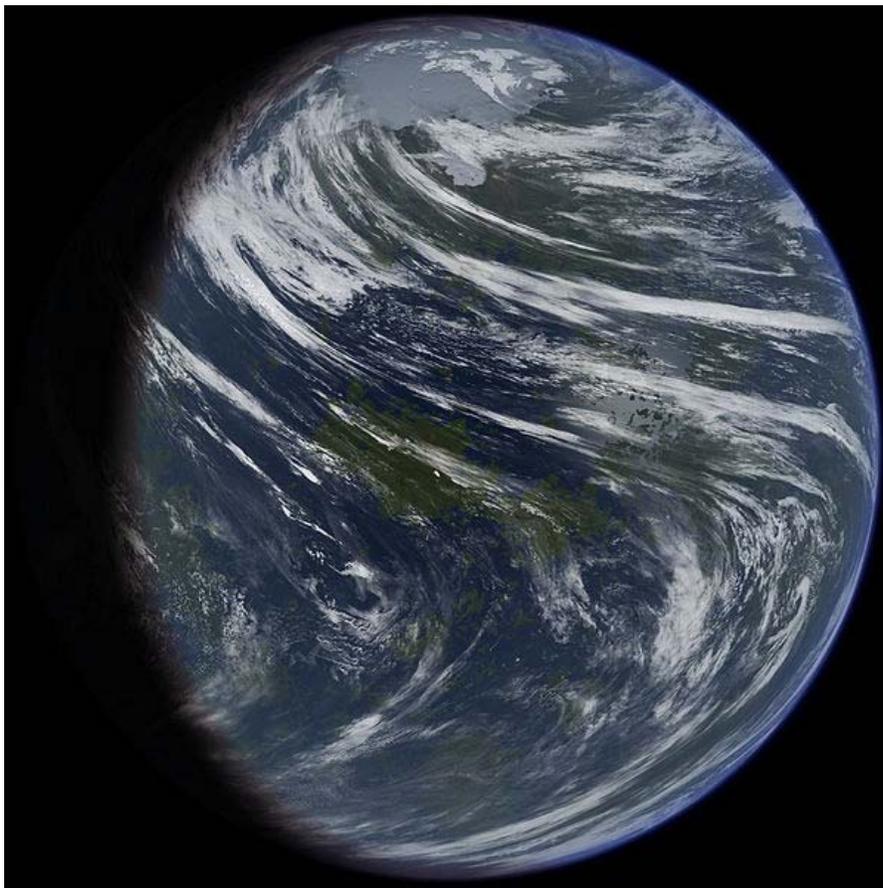
Venus, however, shows that the lack of a magnetosphere does not preclude a dense (albeit dry) atmosphere. A thick atmosphere could also provide solar radiation protection to the surface, similar to Earth's. In the past, Earth has regularly had periods where the magnetosphere changed direction and collapsed for some time.

The lack of a protective magnetic field would also have possible health effects on colonists due to increased cosmic ray flux. The health threat depends on the flux, energy spectrum, and nuclear composition of the rays. The flux and energy spectrum depend on a variety of factors, which are incompletely understood. The Mars Radiation Environment Experiment (MARIE) was launched in 2001 in order to collect more data. Estimates are that humans unshielded in interplanetary space would receive annually roughly 400 to 900 milli-Sieverts (mSv) (compared to 2.4 mSv on Earth) and that a Mars mission (12 months in flight and 18 months on Mars) might expose shielded astronauts to ~500 to 1000 mSv. These doses approach the 1 to 4 Sv career limits advised by the National Council on Radiation Protection and Measurements for Low Earth orbit activities.

Shielding from cosmic rays can be accomplished by placing habitation modules either within lava tubes or under igloo structures built from sintered regolith bricks.

## Chapter-9

# Terraforming of Venus



Artist's conception of a terraformed Venus. The cloud formations are depicted assuming the planet's rotation has not been sped up.

**Terraforming of Venus** is the hypothetical process of engineering the global environment of the planet Venus in such a way as to make it suitable for human habitation. Terraforming Venus was first seriously proposed by the astronomer Carl Sagan in 1961. The minimum adjustments to the existing environment of Venus to support human life would require three major changes to the planet:

- Reducing Venus's 450°C (850°F) surface temperature.
- Eliminating most of the planet's dense 9 MPa (~90 atm) carbon dioxide atmosphere, via removal or conversion to some other form.
- Addition of breathable oxygen to the atmosphere.

These three goals are closely interrelated, since Venus's extreme temperature is due to the greenhouse effect caused by its dense carbon-dioxide atmosphere. In addition, two additional changes would be highly desirable:

- Establishing a day/night light cycle shorter than Venus's current solar day (currently equal to 116.75 Earth days).
- Establishing a planetary magnetic field or substitute for protection against solar and cosmic radiation.

## **Solar shades**

Venus receives about twice the sunlight that Earth does, which is thought to have contributed to its runaway greenhouse effect. Terraforming Venus will likely involve reducing the insolation at Venus' surface to prevent the planet from heating up again.

## **Space based**

Solar shades could be used to reduce the total insolation received by Venus, cooling the planet somewhat. A shade placed in the Sun-Venus  $L_1$  Lagrange point also serves to block the solar wind, removing the radiation exposure problem on Venus.

Construction of a suitably large solar shade is a daunting task. The size of the shade would be four times the diameter of Venus itself if at the  $L_1$  point. This size would necessitate construction in space. There would also be the difficulty of balancing a thin-film shade perpendicular to the Sun's rays at the Sun-Venus Lagrangian point with the incoming radiation pressure, which would tend to turn the shade into a huge solar sail. If the shade were left at the  $L_1$  point, the pressure would add force to the sunward side and necessitate moving the shade even closer to the Sun than the  $L_1$  point.

Modifications to the  $L_1$  solar shade design have been suggested to solve the solar sail problem. One suggested method is to use polar orbiting, solar-synchronous mirrors that reflect light toward the back of the sunshade, from the non-sunward side of Venus. Photon pressure would push the support mirrors to an angle of 30 degrees away from the sunward side.

Paul Birch proposed a slatted system of mirrors near the  $L_1$  point between Venus and the Sun. The shade's panels would not be perpendicular to the sun's rays, but instead at an angle of 30 degrees, such that the reflected light would strike the next panel, negating the photon pressure. Each successive row of panels would be +/- 1 degree off the 30-degree deflection angle, causing the reflected light to be skewed 4 degrees from striking Venus.

Another possibility, suggested by Bradley C. Edwards, is to put into orbit around Venus a belt of material, blocking a portion of sunlight. Multiple thinner belts may be used, and may be composed of a thin net of fibers spaced so that certain wavelengths could not get through while using less material.

Solar shades could also serve as solar power generators. Space-based solar shade techniques, and thin-film solar sails in general, are only in an early stage of development. The vast sizes require a quantity of material that is many orders of magnitude greater than any man-made object that has ever been brought into space or constructed in space.

### **Atmospheric or surface-based**

Cooling could also be effected by placing reflectors in the atmosphere or on the surface. Reflective balloons floating in the upper atmosphere could create shade. The number and/or size of the balloons would necessarily be great. Geoffrey A. Landis has suggested that if enough floating cities were built, they could form a solar shield around the planet, and could simultaneously be used to process the atmosphere into a more desirable form, thus combining the solar shield theory and the atmospheric processing theory with a scalable technology that would immediately provide living space in the Venerian atmosphere. If made from carbon nanotubes (recently fabricated into sheet form) or graphene (a sheet-like carbon allotrope), then the major structural materials can be produced using carbon dioxide gathered in situ from the atmosphere. The recently synthesised amorphous carbonia might prove a useful structural material if it can be quenched to STP conditions, perhaps in a mixture with regular silica glass. According to Birch's analysis such colonies and materials would provide an immediate economic return from colonizing Venus, funding further terraforming efforts.

Increasing the planet's albedo by deploying light color or reflective material on the surface could help keep the atmosphere cool. The amount would be large and would have to be put in place after the atmosphere had been modified already, since Venus's surface is currently completely shrouded by clouds.

An advantage of atmospheric and surface cooling solutions is that they take advantage of existing technology. A disadvantage is that Venus already has highly reflective clouds (giving it an albedo of 0.65), so any approach would have to significantly surpass this to make a difference.

### ***Eliminating the dense carbon dioxide atmosphere***

#### **Biological approaches**

A method proposed in 1961 by Carl Sagan involves the use of genetically engineered bacteria to fix carbon into organic forms. Although this method is still commonly proposed in discussions of Venus terraforming, later discoveries showed it would not be successful. The production of organic molecules from carbon dioxide requires an input of hydrogen, which on Earth is taken from its abundant supply of water but which is nearly

nonexistent on Venus. Since Venus lacks a magnetic field, the upper atmosphere is exposed to direct erosion by solar wind and has lost most of its original hydrogen to space.

Furthermore, any carbon that was bound up in organic molecules would quickly be converted to carbon dioxide again by the hot surface environment. Venus would not begin to cool down until after most of the carbon dioxide has already been removed. Twenty-three years later, in *Pale Blue Dot*, Sagan conceded that his original proposal for terraforming would not work because the atmosphere of Venus is far denser than was known in 1961.

Floating colonies could gradually transform the Venerian atmosphere: for example, their reflectivity could alter the overall albedo of Venus. Colonies could also grow plant matter, if water or another source of hydrogen were imported, which would gradually sequester carbon dioxide in the air. However, it would take an enormous number of such colonies, and large quantities of introduced hydrogen, to have a significant atmospheric impact, as there is over  $1.2 \times 10^{20}$  kg of carbon in Venus's atmosphere.

## **Introduction of hydrogen**

Bombarding Venus with hydrogen, possibly from some outer solar system source, and reacting with carbon dioxide, could produce elemental carbon (graphite) and water by the Bosch reaction. It would take about  $4 \times 10^{19}$  kg of hydrogen to convert the whole Venerian atmosphere. (Loss of hydrogen due to the solar wind is unlikely to be significant on the timescale of terraforming.) Due to the relatively flat surface, this water would cover about 80% of the surface compared to 70% for Earth, even though it would amount to only roughly 10% of the water found on Earth.

The remaining atmosphere, at around 3 bars (about three times that of Earth), will mainly be composed of nitrogen, some of which will dissolve into the new oceans of water, reducing atmospheric pressure further, in accordance with Henry's law.

## **Capture in carbonates**

Bombardment of Venus with refined magnesium and calcium metal could sequester carbon dioxide in the form of calcium and magnesium carbonates. About  $8 \times 10^{20}$  kg of calcium or  $5 \times 10^{20}$  kg of magnesium would be required, which would entail a great deal of mining and mineral refining.  $8 \times 10^{20}$  kg is a few times the mass of the asteroid 4 Vesta (more than 300 miles in diameter).

Modelling by Mark Bullock of Venus' atmospheric evolution suggests that existing surface minerals, particularly calcium and magnesium oxides, could serve as a sink of carbon dioxide and sulphur dioxide. If these could be exposed to the atmosphere then the planet would cool and its atmospheric pressure decline somewhat. One of the possible end states modelled by Bullock was a 43 bar atmosphere and 400 K surface temperature.

## **Direct liquefaction and sequestration**

Birch's proposal involves using a solar shade to cool Venus down sufficiently to permit liquefaction, from a temperature less than 304.18 K and partial pressures of CO<sub>2</sub> down to 73.8 bar (carbon dioxide's critical point) and then down to 5.185 bar and 216.85 K (carbon dioxide's triple point). Below that temperature, freezing of atmospheric carbon dioxide into dry ice will cause it to deposit onto the surface, after which the frozen CO<sub>2</sub> would be buried and maintained in that condition by pressure, or shipped off-world. After this process was complete, the shades could be removed or solettas added, allowing the planet to partially warm again to temperatures comfortable for Earth life. A source of hydrogen or water would still be needed, and some of the remaining 3.5 bar of atmospheric nitrogen would need to be fixed into the soil. Birch suggests disrupting an ice-moon of Saturn and bombarding Venus with its fragments to provide perhaps an average depth of 100 meters of water over the whole planet.

## **Removing atmosphere**

The removal of Venus's atmosphere could be attempted by a variety of methods, possibly in combination. Directly lifting atmospheric gas from Venus into space would likely prove difficult. Venus has sufficiently high escape velocity to make blasting it away with asteroid impacts impractical. Pollack and Sagan calculated in 1993 that an impactor of 700 km diameter striking Venus at greater than 20 km/s, would eject all the atmosphere above the horizon as seen from the point of impact, but since this is less than a thousandth of the total atmosphere and there would be diminishing returns as the atmosphere's density decreased a very great number of such giant impactors would be required. Smaller objects would not work either, requiring even more. The violence of the bombardment could well result in significant outgassing that replaces removed atmosphere. Most of the ejected atmosphere would go into solar orbit near Venus, and, without further intervention, could be captured by Venus' gravitational field and become part of the atmosphere once again.

Removal of atmospheric gas in a more controlled manner could also prove difficult. Venus's extremely slow rotation means that space elevators would be very difficult to construct as the planet's geostationary orbit lies an impractical distance above the surface; and the very thick atmosphere to be removed makes mass drivers useless for removing payloads from the planet's surface. Possible workarounds include placing mass drivers on high-altitude balloons or balloon-supported towers extending above the bulk of the atmosphere, using space fountains, or rotovators.

## ***Rotation***

Venus rotates once every 243 days – by far the slowest rotation period of any of the major planets. A Venerian sidereal day thus lasts more than a Venerian year (243 versus 224.7 Earth days). However, the length of a solar day on Venus is significantly shorter than the sidereal day; to an observer on the surface of Venus the time from one sunrise to the next would be 116.75 days. Nevertheless, Venus's extremely slow rotation rate would

result in extremely long days and nights, which could prove difficult for most known Earth species of plants and animals to adapt to. The slow rotation also likely accounts for the lack of a significant magnetic field.

One proposal is a system of orbiting solar mirrors which might be used to provide sunlight to the night side of Venus and possibly shade to the day side surface. In addition to his suggestion of slatted system of mirrors near the  $L_1$  point between Venus and the Sun, Paul Birch has proposed a rotating soletta mirror in a polar orbit, which would produce a 24-hour light cycle.

Increasing the speed of Venus's rotation would require many orders of magnitude greater amounts of energy than construction of orbiting solar mirrors, or even than the removal of Venus's atmosphere. Recent scientific research suggests that close fly-bys of asteroids or cometary bodies larger than 60 miles across could be used to move a planet in its orbit, or increase the speed of rotation. G. David Nordley has suggested, in fiction, that Venus might be spun-up to a day-length of 30 Earth-days by exporting the atmosphere of Venus into space via mass drivers. This concept was also explored more rigorously by Birch.

## Chapter-10

# Space Colonization



Artist Les Bossinas' 1989 concept of Mars mission

**Space colonization** (also called *space settlement*, *space humanization*, or *space habitation*) is the concept of permanent human habitation outside of Earth. Although hypothetical at the present time, there are many proposals and speculations about the first space colony. It is seen as a long-term goal of some national space programs.

The first space colony may be on the Moon, or on Mars. Ample quantities of all the necessary materials, such as solar energy and water, are on the Moon, Mars, or near Earth asteroids.

In 2005 NASA Administrator Michael Griffin identified space colonization as the ultimate goal of current spaceflight programs, saying:

... the goal isn't just scientific exploration ... it's also about extending the range of human habitat out from Earth into the solar system as we go forward in time ... In the long run a single-planet species will not survive ... If we humans want to survive for hundreds of thousands or millions of years, we must ultimately populate other planets. Now, today the technology is such that this is barely conceivable. We're in the infancy of it. ... I'm talking about that one day, I don't know when that day is, but there will be more human beings who live off the Earth than on it. We may well have people living on the moon. We may have people living on the moons of Jupiter and other planets. We may have people making habitats on asteroids ... I know that humans will colonize the solar system and one day go beyond.

– *Michael D. Griffin*

The NASA Lunar outpost, providing a permanent human presence on the moon, is at the planning stage. There is an ongoing development of technologies that may be used in future space colonization projects.

## **Method**

Building colonies in space would require access to water, food, space, people, construction materials, energy, transportation, communications, life support, simulated gravity, and radiation protection. It is likely the colonies would be located by proximity to such resources. The practice of space architecture seeks to transform spaceflight from a heroic test of human endurance to a normality within the bounds of comfortable experience.

## **Materials**

Colonies on the Moon, Mars, or asteroids could extract local materials. The moon is deficient in volatiles such as argon, helium and compounds of carbon, hydrogen and nitrogen. The LCROSS impactor was targeted at the Cabeus crater which was chosen as having a high concentration of water for the moon. A plume of material erupted in which some water was detected. Anthony Colaprete estimated that the Cabeus crater contains material with 1% water or possibly more. Water ice should also be in other permanently shadowed craters near the lunar poles. Although helium is present only in low concentrations on the moon, where it is deposited into regolith by the solar wind, an estimated million tons of He3 exists over all. It also has industrially significant oxygen, silicon, and metals such as iron, aluminum, and titanium. Launching materials from Earth is expensive, so bulk materials could come from the Moon, a Near-Earth Object (NEO— an asteroid or comet with an orbit near Earth), Phobos, or Deimos, where gravitational forces are much smaller, there is no atmosphere, and there is no biosphere to damage. Many NEOs contain substantial amounts of metals, oxygen, hydrogen, and carbon. Certain NEOs may contain nitrogen.

Farther out, Jupiter's Trojan asteroids are thought to be high in water ice and probably other volatiles.

## Energy

Solar energy in orbit is abundant, reliable, and is commonly used to power satellites today. There is no night in free space, and no clouds or atmosphere to block sunlight. The solar energy available at any distance,  $d$ , from the Sun can be calculated by the formula  $E = 1367/d^2$  watts per square meter, where  $d$  is measured in astronomical units.

Particularly in the weightless conditions of space, sunlight can be used directly, using large solar ovens made of lightweight metallic foil so as to generate thousands of degrees of heat; or reflected onto crops to enable photosynthesis to proceed.

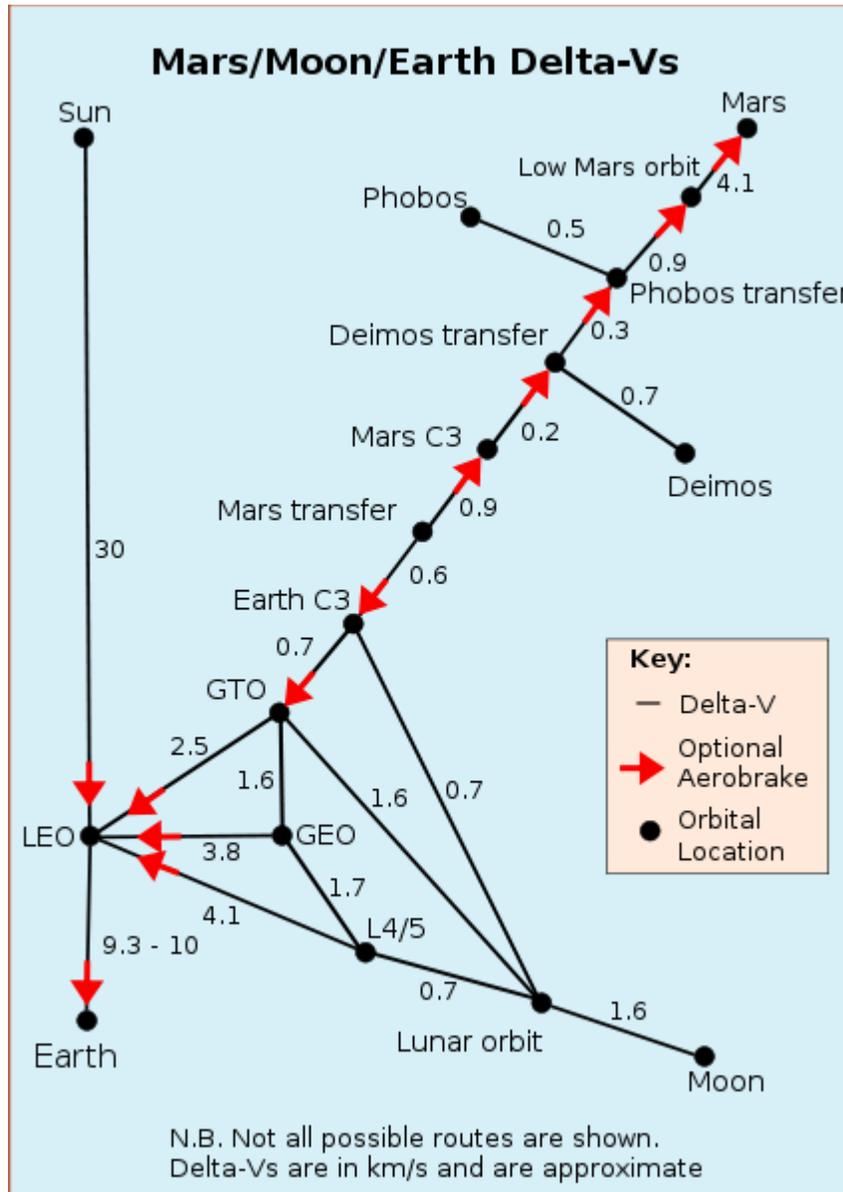
Large structures would be needed to convert sunlight into significant amounts of electrical power for settlers' use. In highly electrified nations on Earth, electrical consumption can average 1 kilowatt/person (or roughly 10 megawatt-hours per person per year.)

Energy may be an eventual export item for space settlements, perhaps using wireless power transmission e.g. via microwave beams to send power to Earth or the Moon. This method has zero emissions, so would have significant benefits such as elimination of greenhouse gases and nuclear waste. Ground area required per watt would be less than conventional solar panels.

The Moon has nights of two Earth weeks in duration and Mars has night, dust, and is farther from the Sun, reducing solar energy available by a factor of about  $\frac{1}{2}$ - $\frac{2}{3}$ , and possibly making nuclear power more attractive on these bodies. Alternatively, energy could be transmitted to the lunar and martian surfaces from solar power satellites.

For both solar thermal and nuclear power generation in airless environments, such as the Moon and space, and to a lesser extent the very thin Martian atmosphere, one of the main difficulties is dispersing the inevitable heat generated. This requires fairly large radiator areas.

## Transportation



Delta-v's in km/s for various orbital maneuvers using conventional rockets. Red arrows show where optional aerobraking can be performed in that particular direction, black numbers give delta-v in km/s that apply in either direction.

## Space access

Transportation to orbit is often the limiting factor in space endeavours. To settle space, much cheaper launch vehicles are required, as well as a way to avoid serious damage to the atmosphere from the thousands, perhaps millions, of launches required. One possibility is the air-breathing hypersonic spaceplane under development by NASA and

other organizations, both public and private. There are also proposed projects such as building a space elevator or a mass driver; or launch loops.

## **Cislunar and solar system travel**

Transportation of large quantities of materials from the Moon, Phobos, Deimos, and Near Earth asteroids to orbital settlement construction sites is likely to be necessary.

Transportation using off-Earth resources for propellant in conventional rockets would be expected to massively reduce in-space transportation costs compared to the present day. Propellant launched from the Earth is likely to be prohibitively expensive for space colonization, even with improved space access costs.

Other technologies such as tether propulsion, VASIMR, ion drives, solar thermal rockets, solar sails, magnetic sails, and nuclear thermal propulsion can all potentially help solve the problems of high transport cost once in space.

For lunar materials, one well-studied possibility is to build mass drivers to launch bulk materials to waiting settlements. Alternatively, lunar space elevators might be employed.

## **Communication**

Compared to the other requirements, communication is easy for orbit and the Moon. A great proportion of current terrestrial communications already passes through satellites. Yet, as colonies further from the earth are considered, communication becomes more of a burden. Transmissions to and from Mars suffer from significant delays due to the speed of light and the greatly varying distance between conjunction and opposition — the lag will range between 7 and 44 minutes — making real-time communication impractical. Other means of communication that do not require live interaction such as e-mail and voice mail systems should pose no problem.

## **Life support**

In space settlements, a closed ecological system must recycle or import all the nutrients without "crashing." The closest terrestrial analogue to space life support is possibly that of the nuclear submarine. Nuclear submarines use mechanical life support systems to support humans for months without surfacing, and this same basic technology could presumably be employed for space use. However, nuclear submarines run "open loop"—extracting oxygen from seawater, and typically dumping carbon dioxide overboard, although they recycle existing oxygen. Recycling of the carbon dioxide has been approached in the literature using the Sabatier process or the Bosch reaction.

The Biosphere 2 project in Arizona has shown that a complex, small, enclosed, man-made biosphere can support eight people for at least a year, although there were many problems. A year or so into the two-year mission oxygen had to be replenished, which strongly suggests that they achieved atmospheric closure.

The relationship between organisms, their habitat and the non-Earth environment can be:

- Organisms and their habitat fully isolated from the environment (examples include artificial biosphere, Biosphere 2, life support system)
- Changing the environment to become a life-friendly habitat, a process called terraforming.
- Changing organisms to become more compatible with the environment.

A combination of the above technologies is also possible.

97–99% of the light energy provided to the plant ends up as heat and needs to be dissipated somehow to avoid overheating the habitat.

## **Radiation protection**

Cosmic rays and solar flares create a lethal radiation environment in space. In Earth orbit, the Van Allen belts make living above the Earth's atmosphere difficult. To protect life, settlements must be surrounded by sufficient mass to absorb most incoming radiation. About five to ten tons of material per square meter of surface area is required. This can be leftover material (slag) from processing lunar soil and asteroids into oxygen, metals, and other useful materials, however it represents a significant obstacle to maneuvering vessels with such massive bulk. Inertia would necessitate powerful thrusters to start or stop rotation, or electric motors to spin two massive portions of a vessel in opposite senses. Shielding material can be stationary around a rotating interior. Hull-metals can also be magnetized to provide additional protection without adding mass.

## **Self-replication**

Self-replication is an optional attribute, but some think it the ultimate goal because it allows a much more rapid increase in colonies, while eliminating costs to and dependence on Earth. It could be argued that the establishment of such a colony would be Earth's first act of self-replication. Intermediate goals include colonies that expect only information from Earth (science, engineering, entertainment) and colonies that just require periodic supply of light weight objects, such as integrated circuits, medicines, genetic material and tools.

## **Population size**

In 2002, the anthropologist John H. Moore estimated that a population of 150–180 would allow normal reproduction for 60 to 80 generations — equivalent to 2000 years.

A much smaller initial population of as little as two female humans should be viable as long as human embryos are available from Earth. Use of a sperm bank from Earth also allows a smaller starting base with negligible inbreeding.

Researchers in conservation biology have tended to adopt the "50/500" rule of thumb initially advanced by Franklin and Soule. This rule says a short-term effective population size ( $N_e$ ) of 50 is needed to prevent an unacceptable rate of inbreeding, while a long-term  $N_e$  of 500 is required to maintain overall genetic variability. The  $N_e = 50$  prescription corresponds to an inbreeding rate of 1% per generation, approximately half the maximum rate tolerated by domestic animal breeders. The  $N_e = 500$  value attempts to balance the rate of gain in genetic variation due to mutation with the rate of loss due to genetic drift.

## **Location**

Location is a frequent point of contention between space colonization advocates.

The location of colonization can be on a physical body or free-flying:

- On a planet, natural satellite, or asteroid
- In orbit around the Earth, Sun, Lagrangian point or other object

## **Planetary locations**

Some planetary colonization advocates cite the following potential locations:

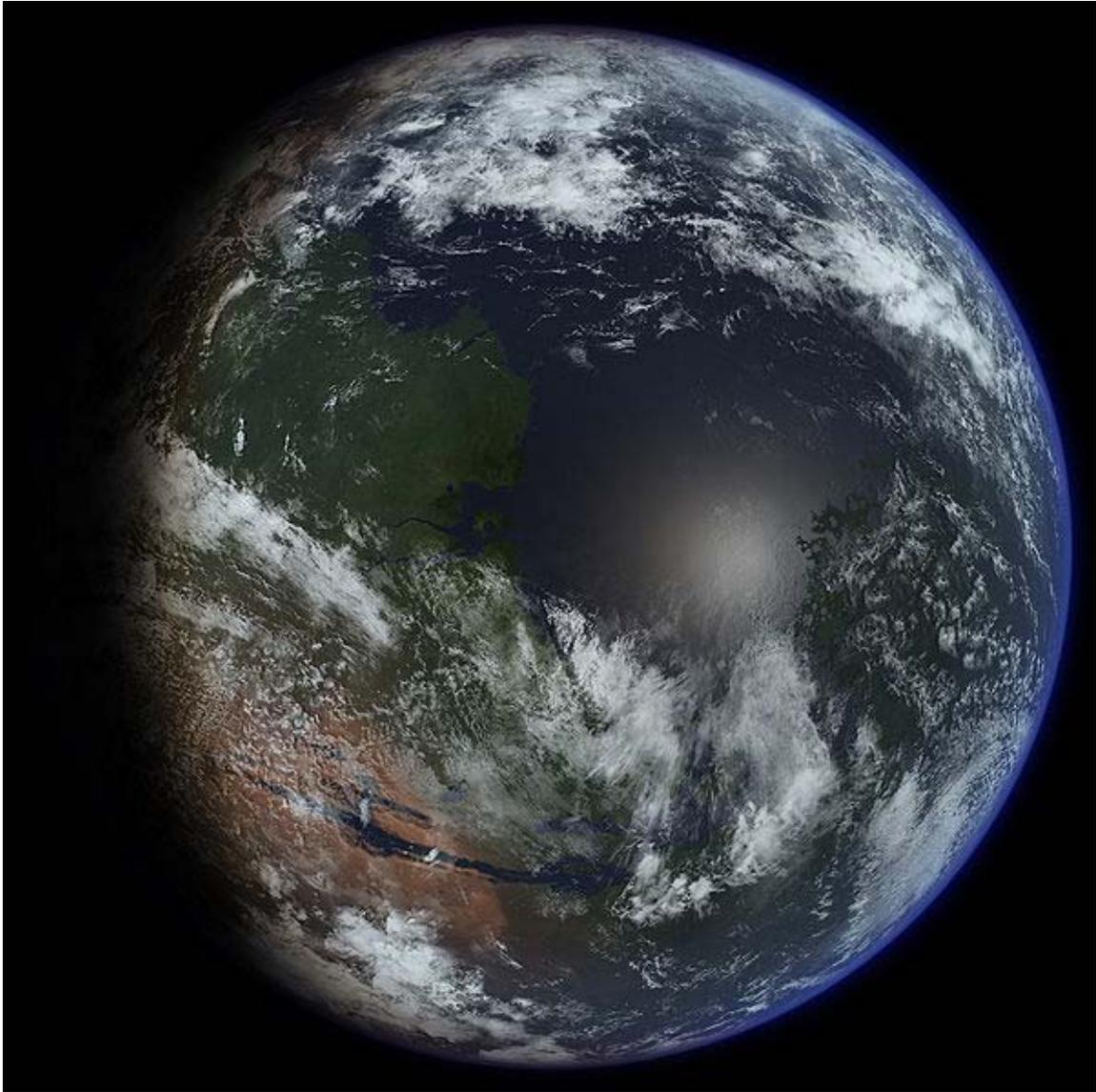
### **Mars**

The surface of Mars is about the same size as the dry land surface of Earth. The ice in Mars' south polar cap, if spread over the planet, would be a layer 12 meters (39 feet) thick and there is carbon (locked as carbon dioxide in the atmosphere).

Mars may have gone through similar geological and hydrological processes as Earth and therefore contain valuable mineral ores. Equipment is available to extract *in situ* resources (e.g., water, air) from the Martian ground and atmosphere. There is interest in colonizing Mars in part because life could have existed on Mars at some point in its history, and may even still exist in some parts of the planet.

However, its atmosphere is very thin (averaging 800 Pa or about 0.8% of Earth sea-level atmospheric pressure); so the pressure vessels necessary to support life are very similar to deep space structures. The climate of Mars is colder than Earth's. Its gravity is only around a third that of Earth's; it is unknown whether this is sufficient to support human beings for extended periods (all long-term human experience to date has been at around Earth gravity or one g).

The atmosphere is thin enough, when coupled with Mars' lack of magnetic field, that radiation is more intense on the surface, and protection from solar storms would require radiation shielding.



An artist's conception of a terraformed Mars (2009)

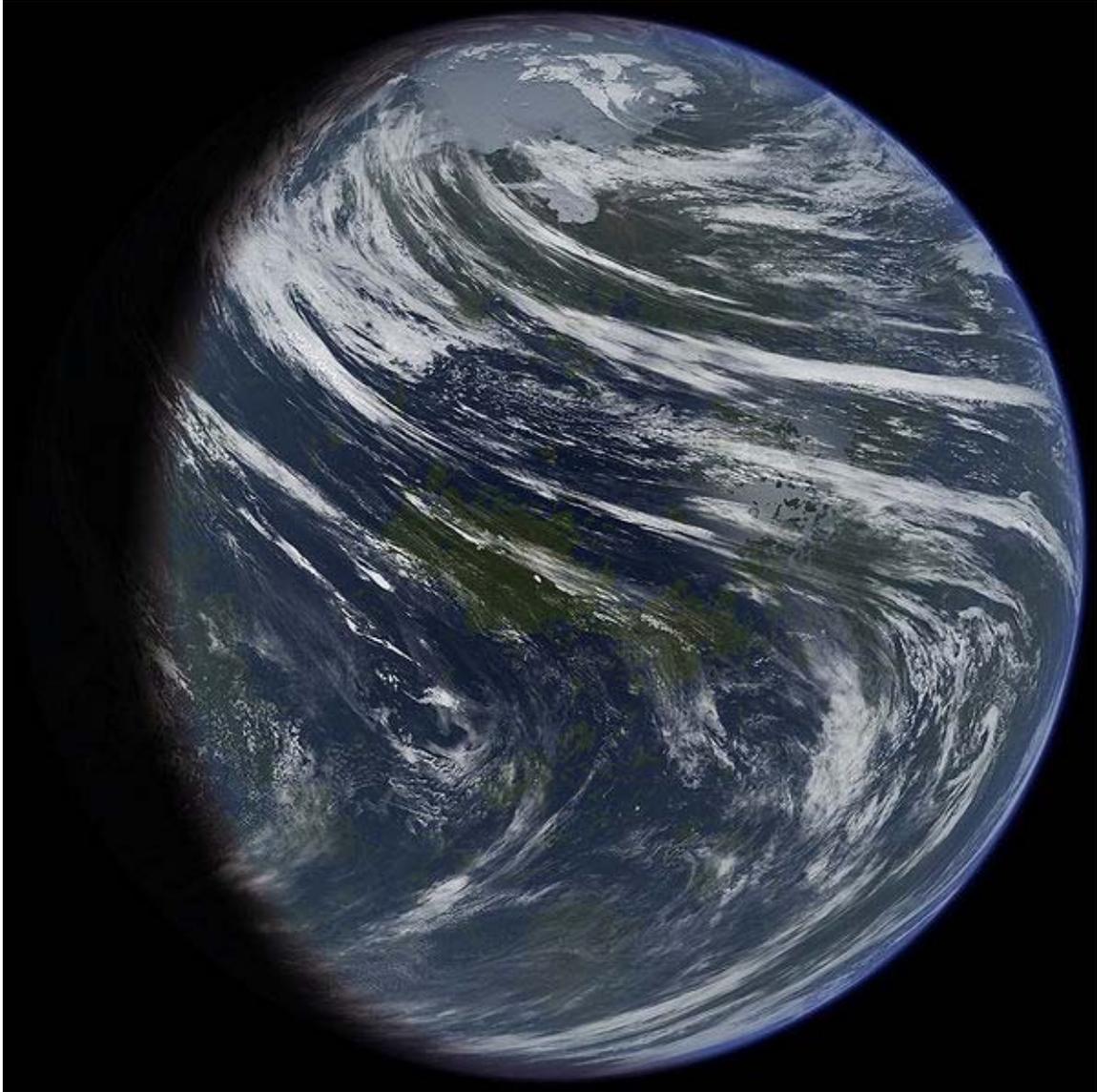
Terraforming Mars would make life outside of pressure vessels on the surface possible. There is some discussion of it actually being done.

## **Mercury**

There is a suggestion that Mercury could be colonized using the same technology, approach and equipment that is used in colonization of the Moon. Such colonies would almost certainly be restricted to the polar regions due to the extreme daytime temperatures elsewhere on the planet.

The recent discovery of ionized water has astounded scientists. This discovery significantly improves the small planet's prospects as a future colony.

## Venus



Artist's impression of a terraformed Venus

While the surface of Venus is far too hot and features atmospheric pressure at least 90 times that at sea level on Earth, its massive atmosphere offers a possible alternate location for colonization. At an altitude of approximately 50 km, the pressure is reduced to a few atmospheres, and the temperature would be between 40–100 °C, depending on the altitude. This part of the atmosphere is probably within dense clouds which contain some sulfuric acid. Even these may have a certain benefit to colonization, as they present a possible source for the extraction of water.

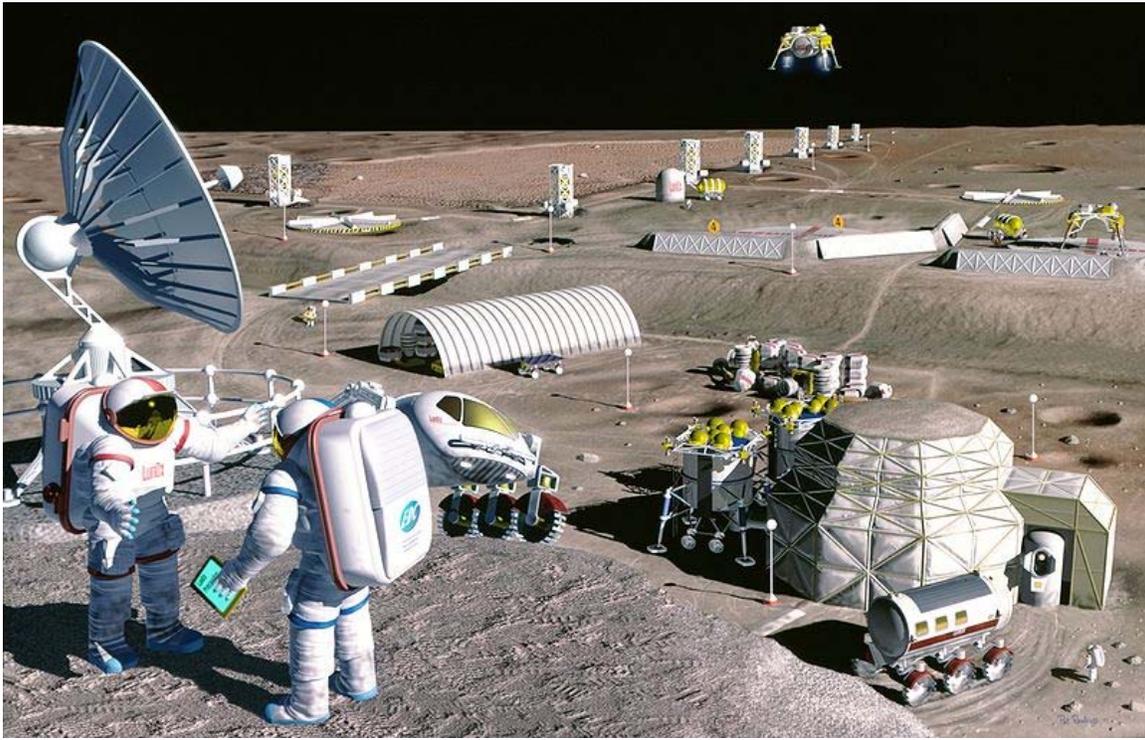
## Gas giants

It may be possible to colonize the three farthest gas giants with floating cities in their atmospheres. By heating hydrogen balloons, large masses can be suspended underneath at roughly Earth gravity. A human colony on Jupiter would be less practical due to its high gravity, escape velocity and radiation. Such colonies could export Helium-3 for use in fusion reactors if they ever become practical. Escape from the gas giant planets (especially Jupiter) seems well beyond current or near-term foreseeable chemical rocket technology however, due to the combination of large velocity and high acceleration needed even to achieve low orbit.

Paul Birch suggested a method of colonizing the gas giants that did not use buoyancy to support the colony in the atmosphere. He suggested a strip colony consisting of an orbital ring extending completely around the planet. It would rotate at the same speed as the planetary atmosphere at the equator and be held above the atmosphere by rotating mass internal to the strip and connected to the strip by only magnetic force. This rotating mass would be isolated from the strip colony by a vacuum. The extent of the strip colony could be such that the bottom edge is within the atmosphere for communication with the planet and extraction of raw materials. In the vacuum environment outside the top edge of the strip, electromagnetic acceleration to or from orbital velocity would provide communication with interplanetary space. This sort of colony would be especially suitable for Saturn, Uranus and Neptune for which the gravitational attraction at the altitude of the visible atmosphere is near one Earth gravity. A robotic levitated equatorial strip colony at Jupiter could allow the extraction of raw materials from that planet.

## Satellite locations

### The Moon



#### Moon colony (1995)

Due to its proximity and familiarity, Earth's Moon is discussed as a target for colonization. It has the benefits of proximity to Earth and lower escape velocity, allowing for easier exchange of goods and services. A drawback of the Moon is its low abundance of volatiles necessary for life such as hydrogen, nitrogen, and carbon. Water ice deposits that exist in some polar craters could serve as a source for these elements. An alternative solution is to bring hydrogen from near earth asteroids and combine it with oxygen extracted from lunar rock.

The moon's low surface gravity is also a concern (it is unknown whether  $1/6g$  is sufficient to support human habitation for long periods).

### Jovian moons - Europa, Callisto and Ganymede

The Artemis Project designed a plan to colonize Europa, one of Jupiter's moons. Scientists were to inhabit igloos and drill down into the European ice crust, exploring any sub-surface ocean. This plan discusses possible use of "air pockets" for human habitation. Europa is considered one of the more habitable bodies in the solar system and so merits investigation as a possible abode for life.

Ganymede is the largest moon in the Solar System. It may be attractive as Ganymede is the only moon with a magnetosphere and so is less irradiated at the surface. The presence of magnetosphere, likely indicates a convecting molten core within Ganymede, which may in turn indicate a rich geologic history for the moon.

NASA performed a study called *HOPE* (Revolutionary Concepts for **H**uman **O**uter **P**lanet **E**xploration) regarding the future exploration of the solar system. The target chosen was Callisto. It could be possible to build a surface base that would produce fuel for further exploration of the solar system.

The three out of four largest moons of Jupiter (Europa, Ganymede and Callisto) have an abundance of volatiles making future colonization possible.

### **Phobos and Deimos**

The moons of Mars may be a target for space colonization. Low delta-v is needed to reach the Earth from Phobos and Deimos, allowing delivery of material to cislunar space, as well as transport around the Martian system. The moons themselves may be suitable for habitation, with methods similar to those for asteroids.

### **Titan, Enceladus, and other Saturnian moons**

Titan is suggested as a target for colonization, because it is the only moon in our solar system to have a dense atmosphere and is rich in carbon-bearing compounds. Robert Zubrin identified Titan as possessing an abundance of all the elements necessary to support life, making Titan perhaps the most advantageous locale in the outer Solar System for colonization, and saying "In certain ways, Titan is the most hospitable extraterrestrial world within our solar system for human colonization".

Enceladus is a small, icy moon orbiting close to Saturn, notable for its extremely bright surface and the geyser-like plumes of ice and water vapor that erupt from its southern polar region. If Enceladus has liquid water, it joins Mars and Jupiter's moon Europa as one of the prime places in the solar system to look for extraterrestrial life and possible future settlements.

Other large satellites: Rhea, Iapetus, Dione, Tethys, and Mimas, all have large quantities of volatiles, which can be used to support settlement.

### **Moons of Uranus, Neptune's Triton, and beyond**

The five large moons of Uranus (Miranda, Ariel, Umbriel, Titania and Oberon) and Triton - Neptune's moon, although very cold, have large amounts of frozen water and other volatiles and could potentially be settled, only they would require a lot of nuclear power to sustain the habitats. Triton's thin atmosphere also contains some nitrogen and even some frozen nitrogen on the surface (the surface temperature is 38 K or about -391° Fahrenheit). Pluto is estimated to have a very similar structure to Triton.

## **Asteroids**

### **Near Earth Asteroids**

Many small asteroids in orbit around the Sun have the advantage that they pass closer than Earth's moon several times per decade. In between these close approaches to home, the asteroid may travel out to a furthest distance of some 350,000,000 kilometers from the Sun (its aphelion) and 500,000,000 kilometers from Earth.

### **Main Belt Asteroids**

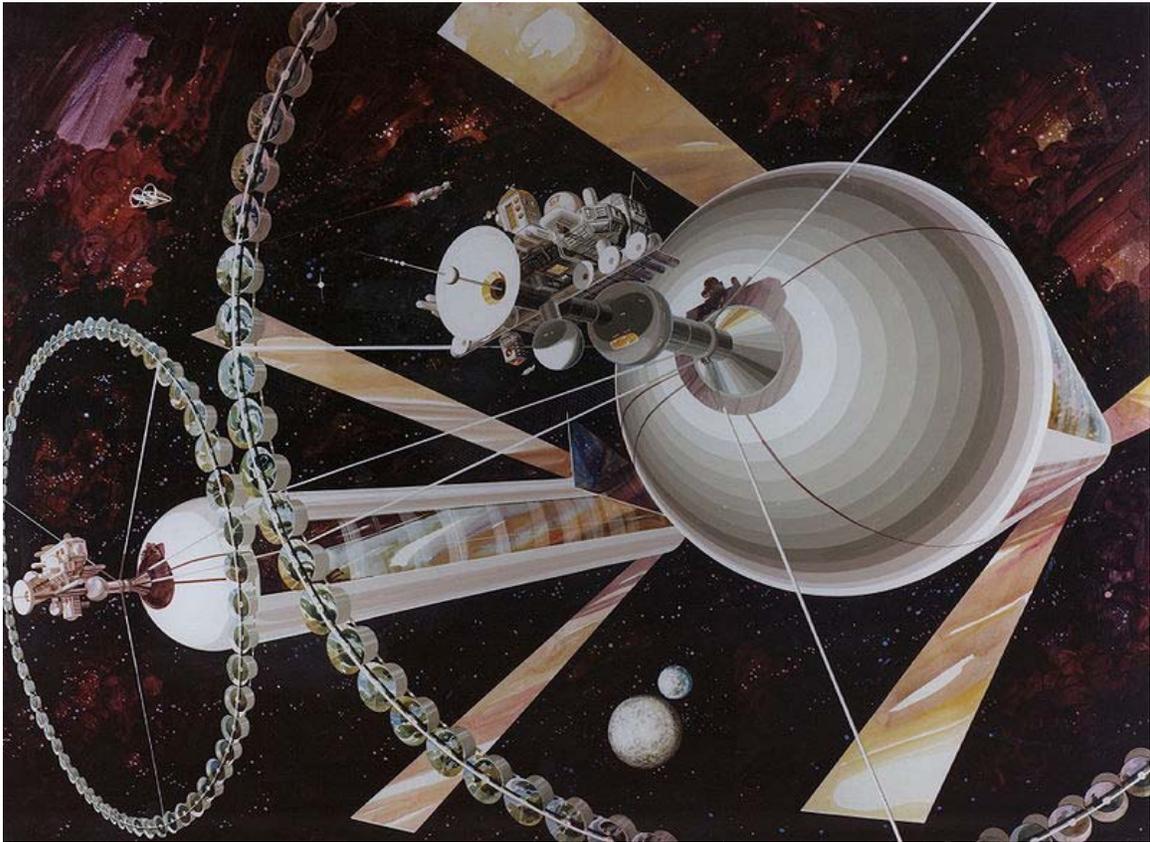
Colonization of asteroids would require space habitats. The asteroid belt has significant overall material available, the largest object being Ceres, although it is thinly distributed as it covers a vast region of space. Unmanned supply craft should be practical with little technological advance, even crossing 1/2 billion kilometers of cold vacuum. The colonists would have a strong interest in assuring that their asteroid did not hit Earth or any other body of significant mass, but would have extreme difficulty in moving an asteroid of any size. The orbits of the Earth and most asteroids are very distant from each other in terms of delta-v and the asteroidal bodies have enormous momentum. Rockets or mass drivers can perhaps be installed on asteroids to direct their path into a safe course.

### **Ceres**

Ceres is a dwarf planet in the main asteroid belt, comprising about one third the mass of the whole belt and being the sixth largest body in the inner Solar System by mass and volume. Being the largest body in the asteroid belt, Ceres could become the main base and transport hub for future asteroid mining infrastructure, allowing mineral resources to be transported further to Mars, the Moon and Earth. It may be possible to Paraterraform Ceres, making life easier for the colonists. Given its low gravity and fast rotation, a space elevator would also be practical.

**Free space**

**Space habitats**



O'Neill cylinders space colony (Island Three design from the 1970s)



Artist's conception of a space habitat called the Stanford torus, by Don Davis (1976).

Locations in space would necessitate a space habitat, also called space colony and orbital colony, or a space station which would be intended as a permanent settlement rather than as a simple waystation or other specialized facility. They would be literal "cities" in space, where people would live and work and raise families. Many designs have been proposed with varying degrees of realism by both science fiction authors and scientists.

A space habitat would serve as a proving ground for a generation ship which could function as a long-term home for hundreds or thousands of people. Such a space habitat could be isolated from the rest of humanity but near enough to Earth for help. This would test if thousands of humans can survive on their own before sending them beyond the reach of help.

### **Earth orbit**

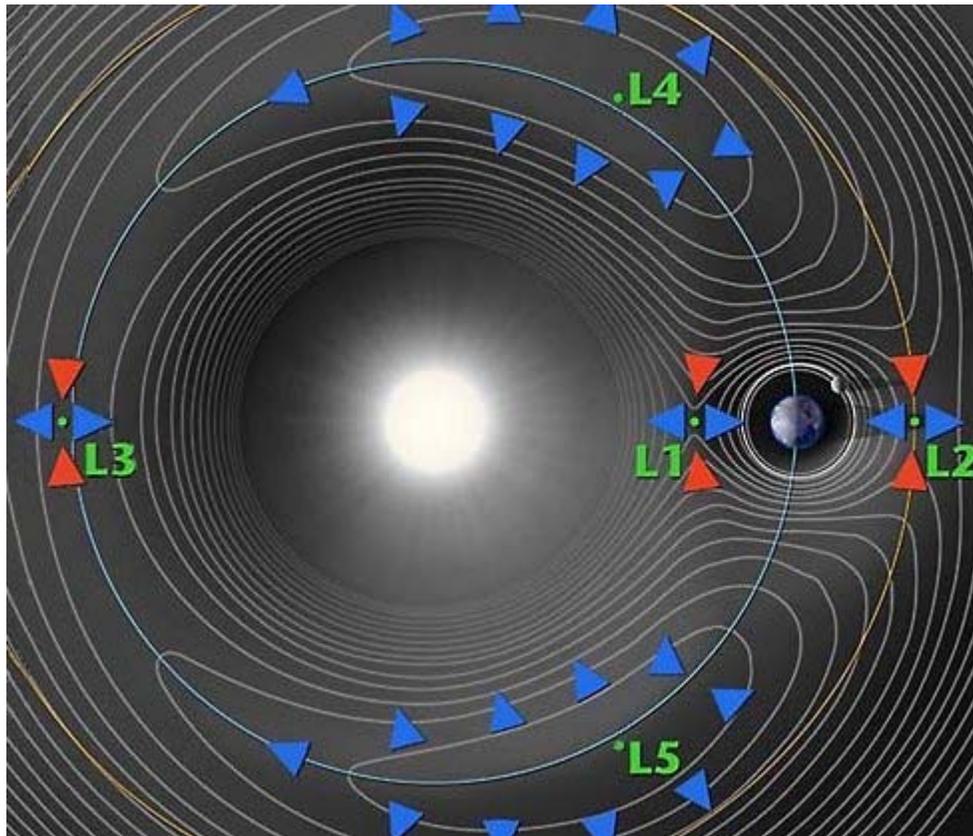
Compared to other locations, Earth orbit has substantial advantages and one major, but solvable, problem. Orbits close to Earth can be reached in hours, whereas the Moon is days away and trips to Mars take months. There is ample continuous solar power in high Earth orbits, whereas all planets lose sunlight at least half the time. Weightlessness makes construction of large colonies considerably easier than in a gravity environment. Astronauts have demonstrated moving multi-ton satellites by hand. 0g recreation is

available on orbital colonies, but not on the Moon or Mars. Finally, the level of (pseudo-) gravity is controlled at any desired level by rotating an orbital colony. Thus, the main living areas can be kept at 1 g, whereas the Moon has 1/6 g and Mars 1/3 g. It's not known what the minimum g-force is for ongoing health but 1 g is known to ensure that children grow up with strong bones and muscles.

The main disadvantage of orbital colonies is lack of materials. These may be expensively imported from the Earth, or more cheaply from extraterrestrial sources, such as the Moon (which has ample metals, silicon, and oxygen), Near Earth Asteroids, comets, or elsewhere. Other disadvantages of orbital colonies are orbital decay, and atmospheric pollution in the case of Earth.

As of 2009, the International Space Station provides a temporary, yet still non-autonomous, human presence in Low Earth orbit.

### Lagrange points



A contour plot of the effective potential of the Sun and Earth, showing the five Lagrange points.

Another near-Earth possibility are the five Earth-Moon Lagrange points. Although they would generally also take a few days to reach with current technology, many of these

points would have near-continuous solar power capability since their distance from Earth would result in only brief and infrequent eclipses of light from the Sun.

The five Earth-Sun Lagrange points would totally eliminate eclipses, but only  $L_1$  and  $L_2$  would be reachable in a few days' time. The other three Earth-Sun points would require months to reach.

However, the fact that Lagrange points  $L_4$  and  $L_5$  tend to collect dust and debris, while  $L_1$ - $L_3$  require active station-keeping measures to maintain a stable position, make them somewhat less suitable places for habitation than was originally believed. Additionally, the orbit of  $L_2$  -  $L_5$  takes them out of the protection of the Earth's magnetosphere for approximately two-thirds of the time, exposing them to the health threat from cosmic rays.

## **Statites**

Statites or "static satellites" employ solar sails to position themselves in orbits that gravity alone could not accomplish. Such a solar sail colony would be free to ride solar radiation pressure and travel off the ecliptic plane. Navigational computers with an advanced understanding of flocking behavior could organize several statite colonies into the beginnings of the true "swarm" concept of a Dyson sphere.

## ***Outside the solar system***

Looking beyond our solar system, there are billions of potential stars with possible colonization targets.

The long-term survival of the human race is at risk as long as it is confined to a single planet. Sooner or later, disasters such as an asteroid collision or nuclear war could wipe us all out. But once we spread out into space and establish independent colonies, our future should be safe. There isn't anywhere like the Earth in the solar system, so we would have to go to another star.

*– Stephen Hawking, Physicist*

## **Interstellar travel**

Many scientific papers have been published about interstellar travel. Given sufficient travel time and engineering work, both unmanned and generational voyages seem possible, though representing a very considerable technological and economic challenge unlikely to be met for some time, particularly for manned probes.

The main difficulty is the vast distances that have to be covered. This means that a very high speed is needed. Otherwise, the time involved, with most realistic propulsion methods, would be from decades to millennia. Hence an interstellar ship would be much

more severely exposed to the hazards found in interplanetary travel, including hard vacuum, radiation, weightlessness, and micrometeoroids.

## **Intergalactic travel**

Intergalactic travel, as it pertains to humans, is impractical by modern engineering ability and is considered highly speculative. It would require the available means of propulsion to become advanced far beyond what is currently thought possible to engineer in order to bring a large craft close to the speed of light. Unless the craft were capable of reaching extreme relativistic speeds, another obstacle would be to navigate the spacecraft between galaxies and succeed in reaching any chosen galaxy, star, planet or other body, as this would need an improvement over current understanding of galactic movements and their coordination. The craft would have to be of considerable size, without reaching speeds with noteworthy relativistic effect as mentioned above it would also need a life support system and structural design able to support human life through thousands of generations and last the millions of years required, including the propulsion system—which would have to work perfectly the millions of years after it was built to slow down the machine for its final approach. Even for unmanned probes which would be much lighter in mass, the problem exists that the information they send can only travel at light speed, which would mean millions of years just to receive the data they send.

Current physics states that an object within space-time cannot exceed the speed of light, which seemingly limits any object to the millions of years it would at best take for a craft traveling near the speed of light to reach any remote galaxy. Science fiction frequently employs speculative concepts such as wormholes and hyperspace as more practical means of intergalactic travel to work around this issue. However, some scientists are optimistic in regard to future research into techniques considered even in concept sheer science fiction in the past.

## **Starship**

Space colonization technology could in principle allow human expansion at high, but sub-relativistic speeds, substantially less than the speed of light,  $c$ . An interstellar colony ship would be similar to a space habitat, with the addition of major propulsion capabilities and independent energy generation. Hypothetical starship concepts proposed both by scientists and in hard science fiction include:

- A generation ship would travel much slower than light, with consequent interstellar trip times of many decades or centuries. The crew would go through generations before the journey is complete, so that none of the initial crew would be expected to survive to arrive at the destination, assuming current human lifespans.
- A sleeper ship, in which most or all of the crew spend the journey in some form of hibernation or suspended animation, allowing some or all who undertake the journey to survive to the end.

- An Embryo-carrying Interstellar Starship (EIS), much smaller than a generation ship or sleeper ship, transporting human embryos or DNA in a frozen or dormant state to the destination. (Obvious biological and psychological problems in birthing, raising, and educating such voyagers, neglected here, may not be fundamental.)
- A nuclear fusion or fission powered ship (e.g., ion drive) of some kind, achieving velocities of up to perhaps 10%  $c$  permitting one-way trips to nearby stars with durations comparable to a human lifetime.
- A Project Orion-ship, a nuclear-powered concept proposed by Freeman Dyson which would use nuclear explosions to propel a starship. A special case of the preceding nuclear rocket concepts, with similar potential velocity capability, but possibly easier technology.
- Laser propulsion concepts, using some form of beaming of power from the Solar System might allow a light-sail or other ship to reach high speeds, comparable to those theoretically attainable by the fusion-powered electric rocket, above. These methods would need some means, such as supplementary nuclear propulsion, to stop at the destination, but a hybrid (light-sail for acceleration, fusion-electric for deceleration) system might be possible.

The above concepts all appear limited to high, but still sub-relativistic speeds, due to fundamental energy and reaction mass considerations, and all would entail trip times which might be enabled by space colonization technology, permitting self-contained habitats with lifetimes of decades to centuries. Yet human interstellar expansion at average speeds of even 0.1% of  $c$  would permit settlement of the entire Galaxy in less than one half of a galactic rotation period of  $\sim 250,000,000$  years, which is comparable to the timescale of other galactic processes. Thus, even if interstellar travel at near relativistic speeds is never feasible (which cannot be clearly determined at this time), the development of space colonization could allow human expansion beyond the Solar System without requiring technological advances that cannot yet be reasonably foreseen. This could greatly improve the chances for the survival of intelligent life over cosmic timescales, given the many natural and human-related hazards that have been widely noted.

The star Tau Ceti, about twelve light years away, has an abundance of cometary and asteroidal material in orbit around it. These materials could be used for the construction of space habitats for human settlement.

### ***Terrestrial analogues to space colonies***

The most famous attempt to build an analogue to a self-sufficient colony is Biosphere 2, which attempted to duplicate Earth's biosphere.

Many space agencies build testbeds for advanced life support systems, but these are designed for long duration human spaceflight, not permanent colonization.

Remote research stations in inhospitable climates, such as the Amundsen-Scott South Pole Station or Devon Island Mars Arctic Research Station, can also provide some practice for off-world outpost construction and operation. The Mars Desert Research Station has a habitat for similar reasons, but the surrounding climate is not strictly inhospitable.

Nuclear Submarines provide an example of conditions encountered in artificial space environment. Crews of these vessels often spend long periods (6 months or more) submerged during their deployments. However, the submarine environment provides a somewhat open life support system since the vessel can replenish supplies of fresh water and oxygen from seawater.

Other examples of small groups in isolated living conditions are record long-distance flights, long-distance (single-handed) sails, oil platforms, prisons, bunkers, small islands and underground bases.

The study of terrestrial analogues is also a central focus in space architecture.

## **Literature**

The literature for space colonization began in 1869 when Edward Everett Hale wrote about an inhabited artificial satellite.

The Russian schoolmaster and physicist Konstantin Tsiolkovsky foresaw elements of the space community in his book *Beyond Planet Earth* written about 1900. Tsiolkovsky had his space travelers building greenhouses and raising crops in space.

Others have also written about space colonies as Lasswitz in 1897 and Bernal, Oberth, Von Pirquet and Noordung in the 1920s. Wernher von Braun contributed his ideas in a 1952 *Colliers* article. In the 1950s and 1960s, Dandridge M. Cole published his ideas.

Another seminal book on the subject was the book *The High Frontier: Human Colonies in Space* by Gerard K. O'Neill in 1977 which was followed the same year by *Colonies in Space* by T. A. Heppenheimer.

M. Dyson wrote *Home on the Moon; Living on a Space Frontier* in 2003; Peter Eckart wrote *Lunar Base Handbook* in 2006 and then Harrison Schmitt's *Return to the Moon* written in 2007.

## **Debate**

### **Justification**

In 2001, the space news website Space.com asked Freeman Dyson, J. Richard Gott and Sid Goldstein for reasons why some humans should live in space. Their answers were:

- Spread life and beauty throughout the Universe
- Ensure the survival of our species
- Make money through new forms of space commercialization such as solar power satellites, asteroid mining, and space manufacturing
- Save the environment of Earth by moving people and industry into space
- Provide entertainment value in order to distract from immediate surroundings, space tourism
- Ensure sufficient supply of rare materials, including from the Outer Solar System – natural gas (in connection with expected worldwide hydrocarbons peak) and drinking water (in connection with expected worldwide water shortage)

Nick Bostrom argued that from a utilitarian perspective space colonization should be a chief goal as it would enable a very large population living for a very long period of time (possibly billions of years) which would produce an enormous amount of utility (or happiness). He claims that it is more important to reduce existential risks to increase the probability of eventual colonization rather than to accelerate technological development so that space colonization could happen sooner.

Louis J. Halle, formerly of the United States Department of State, wrote in *Foreign Affairs* (Summer 1980) that the colonization of space will protect humanity in the event of global nuclear warfare.

The scientist Paul Davies also supports the view that if a planetary catastrophe threatens the survival of the human species on Earth, a self-sufficient colony could "reverse-colonize" the Earth and restore human civilization.

The author and journalist William E. Burrows and the biochemist Robert Shapiro proposed a private project, the Alliance to Rescue Civilization, with the goal of establishing an off-Earth backup of human civilization.

## **Objections**

Colonizing space would require massive amounts of financial, physical and human capital devoted to research, development, production, and deployment.

The fundamental problem of public things, needed for survival, such as space programs, is the free rider problem. Convincing the public to fund such programs would require additional self-interest arguments: If the objective of space colonization is to provide a "backup" in case everyone on Earth is killed, then why should someone on Earth pay for something that is only useful after they're dead? This assumes that space colonization is not widely acknowledged as a sufficiently valuable social goal.

Other objections include concern about creating a culture in which humans are no longer seen as human, but rather as material assets. The issues of human dignity, morality, philosophy, culture, bioethics, and the threat of megalomaniac leaders in these new

"societies" would all have to be addressed in order for space colonization to meet the psychological and social needs of people living in isolated colonies or generation ships.

As an alternative or addendum for the future of the human race, many science fiction writers have focused on the realm of the 'inner-space', that is the computer aided exploration of the human mind and human consciousness.

## **Counter arguments**

### **The argument of need**

The population of Earth continues to increase, while its carrying capacity and available resources do not. If the resources of space are opened to use and viable life-supporting habitats can be built, the Earth will no longer define the limitations of growth. On the other hand, extrapolations made using available figures for population growth, shows that the population of Earth will stop growing around 2070.

Furthermore, even if humanity manages to avoid devastating Earth through war, pestilence, pollution, global cooling, global warming, and even cometary impacts, the Earth will ultimately become uninhabitable by the heating from the Sun as it ages. If humanity has not made permanent habitations in space by the time any one of these incidents occurs, it may very well go extinct.

“ Maybe the reason civilizations don't get around to colonizing other planets is that there's a narrow window when they have the tools, population and will to do so, and the window usually closes on them.”

--John Tierney

"If it's true that civilizations normally go extinct because they get stuck on their home planets, then the odds are against us"

--John Tierney

”

### **The argument of benefits**

Detractors of the development of permanent space colonies and infrastructure often cite the very high initial investment costs of space colonies and permanent space

infrastructure yet they ignore all potential returns on that investment. The long-term vision of developing space infrastructure is that it will provide long-term benefits far in excess of the initial start-up costs. Therefore, such a development program should be viewed more as a long-term investment and not like current social spending programs that incur spending commitments but provide little or no return on that investment.

Because current space launch costs are so high (on the order of \$4,000 to \$40,000 / kg launched into orbit) any serious plan to develop space infrastructure at a reasonable cost must include developing the ability of that infrastructure to manufacture most or all of its requirements plus those for permanent human habitation in space. Therefore, the initial investments must be made in the development of the initial capacity to provide these necessities: Materials, Energy, Transportation, Communication, Life support, Radiation protection, Self-replication, and Population.

Once the needs of the permanent settlements have been met, any additional production capacity could be use to either extend that initial infrastructure (a concept commonly called "bootstrapping") or traded back to Earth in payment of the initial investment or in exchange for goods more easily manufactured on the Earth.

Although some items of the infrastructure requirements above can already be easily produced on the Earth and would therefore not be very valuable as trade items (oxygen, water, base metal ores, silicates, etc.), other high value items are more abundant, more easily produced, of higher quality, or can only be produced in space. These would provide (over the long-term) a very high return on the initial investment in space infrastructure.

Some of these high trade value goods include precious metals, gem stones, power, solar cells, ball bearings, semi-conductors, and pharmaceuticals.

“ ... the smallest Earth-crossing asteroid 3554 Amun is a mile-wide (2 km) lump of iron, nickel, cobalt, platinum, and other metals; it contains 30 times as much metal as Humans have mined throughout history, although it is only the smallest of dozens of known metallic asteroids and worth perhaps US\$ 20 trillion if mined slowly to meet demand at 2001 market prices. ”

“ In the 2,900 km<sup>3</sup> of Eros, there is more aluminium, gold, silver, zinc and other base and precious metals than have ever been excavated in history or indeed, could ever be excavated from the upper layers of the Earth's crust. ”

The main impediments to commercial exploitation of these resources are the very high cost of initial investment, the very long period required for the expected return on those investments (estimated to be 50 years or more by some), and because it has never been done before - the high-risk nature of the investment.

### **The argument of nationalism**

Space proponents counter this argument by pointing out that humanity as a whole has been exploring and expanding into new territory since long before Europe's colonial period, going back into prehistory (the nationalist argument also ignores multinational cooperative space efforts); that seeing the Earth as a single, discrete object instills a powerful sense of the unity, connectedness of the human environment, and of the immateriality of political borders; and that in practice, international collaboration in space has shown its value as a unifying and cooperative endeavor.

### **Advocacy**

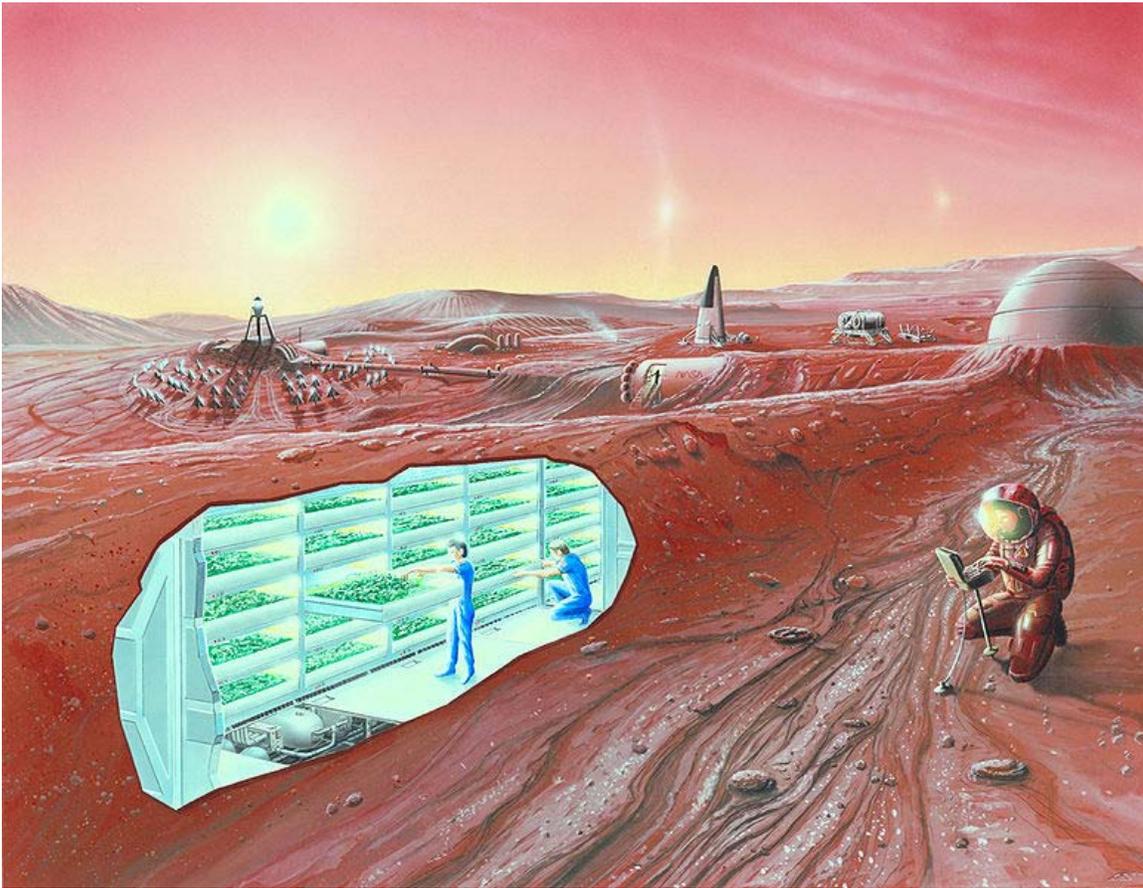
Space advocacy organizations include:

- The Space Studies Institute was founded by Gerard K. O'Neill to fund the study of space habitats.
- The Space Frontier Foundation promotes strong free market, capitalist views about space development.
- The Artemis Project plans to set up a private lunar surface station.
- The British Interplanetary Society, founded in 1933, is the world's longest established space society.
- The Living Universe Foundation has a detailed plan in which the entire galaxy is colonized.
- The Colonize the Cosmos site advocates orbital colonies.
- The Mars Society promotes Robert Zubrin's Mars Direct plan and the settlement of Mars.
- The National Space Society is an organization with the vision of "people living and working in thriving communities beyond the Earth."
- The Planetary Society is the largest space interest group, but has an emphasis on robotic exploration and the search for extraterrestrial life.

- The Space Settlement Institute is searching for ways to make space colonization happen in our lifetimes.
- Students for the Exploration and Development of Space (SEDS) is a student organization founded in 1980 at MIT and Princeton.
- Foresight Nanotechnology Institute – The space challenge.
- The Alliance to Rescue Civilization plans to establish backups of human civilization on the Moon and other locations away from Earth.

## Chapter-11

# Colonization of Mars



An artist's conception of the colonization of Mars, with a cutaway showing part of the interior (NASA Ames, 2005)

The **colonization of Mars** by humans is the focus of speculation and serious study because the surface conditions and availability of water on Mars make it arguably the most hospitable planet in the solar system other than Earth. The Moon has been proposed as the first location for human colonization but Mars has an atmosphere, giving it the potential capacity to host human and other organic life.

## ***Relative similarity to Earth***

The Earth is very like its "sister planet" Venus in bulk composition, size and surface gravity but Mars' similarities to Earth are arguably more compelling when considering colonization. These include:

- The Martian day (or **sol**) is very close to Earth's. A Mars solar day is 24 hours 39 minutes 35.244 seconds.
- Mars has a surface area that is 28.4% of Earth's, only slightly less than the amount of dry land on Earth (which is 29.2% of Earth's surface). Mars has half the radius of Earth and only one-tenth the mass. This means that it has a smaller volume (~15%) and lower average density than Earth.
- Mars has an axial tilt of 25.19°, compared with Earth's 23.44°. As a result, Mars has seasons much like Earth, though they last nearly twice as long because the Martian year is about 1.88 Earth years. The Martian north pole currently points at Cygnus, not Ursa Minor.
- Mars has an atmosphere. Although it is very thin (about 0.7% of Earth's atmosphere) it provides some protection from solar and cosmic radiation and has been used successfully for aerobraking of spacecraft.
- Recent observations by NASA's Mars Exploration Rovers, ESA's Mars Express and NASA's Phoenix Lander confirm the presence of water ice on Mars. Mars appears to have significant quantities of all the elements necessary to support Earth-based life.

## ***Differences from Earth***

- The surface gravity on Mars is 0.38 of that on Earth. It is not known if this is enough to prevent the health problems associated with weightlessness.
- Mars is much colder than Earth, with a mean surface temperature of -63°C and a low of -140°C. The lowest temperature ever recorded on Earth was -89.2°C, in Antarctica.
- There are no standing bodies of liquid water on the surface of Mars.
- Because Mars is further from the Sun, the amount of solar energy reaching the upper atmosphere (the solar constant) is less than half of what reaches the Earth's upper atmosphere or the Moon's surface. However, the solar energy that reaches the surface of Mars is not impeded by a thick atmosphere like on Earth.
- Mars' orbit is more eccentric than Earth's, exacerbating temperature and solar constant variations.

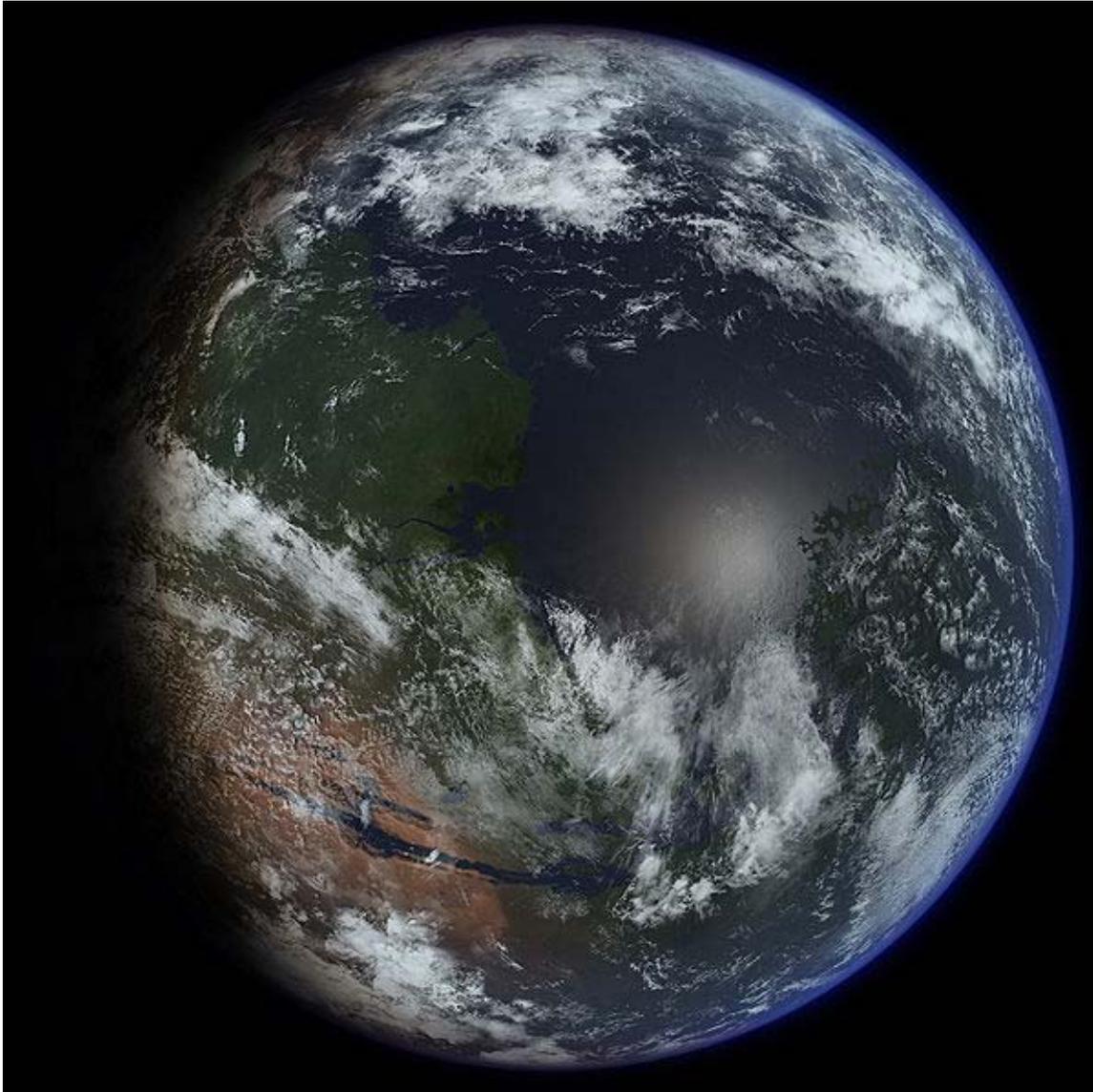
- The atmospheric pressure on Mars is ~6 mbar, far below the Armstrong Limit (61.8 mbar) at which people can survive without pressure suits. Since terraforming cannot be expected as a near-term solution, habitable structures on Mars would need to be constructed with pressure vessels similar to spacecraft, capable of containing a pressure between a third and a whole bar.
- The Martian atmosphere consists mainly of carbon dioxide. Because of this, even with the reduced atmospheric pressure, the partial pressure of CO<sub>2</sub> at the surface of Mars is some 52 times higher than on Earth. It also has significant levels of carbon monoxide.
- Mars has a very weak magnetosphere, so it deflects solar winds poorly.

### ***Habitability***

Conditions on the surface of Mars are much closer to habitability than the surface of any other known planet or moon, as seen by the extremely hot and cold temperatures on Mercury, the furnace-hot surface of Venus, or the cryogenic cold of the outer planets and their moons. Only the cloud tops of Venus are closer in terms of habitability to Earth than Mars is. There are natural settings on Earth where humans have explored that match most conditions on Mars. The highest altitude reached by a manned balloon ascent, a record set in May 1961, was 34,668 meters (113,740 feet). The pressure at that altitude is about the same as on the surface of Mars. Extreme cold in the Arctic and Antarctic match all but the most extreme temperatures on Mars.

NASA Deputy Administrator Shana Dale said, "We also hope to discover if Mars can provide a second home for humans—an extension of our civilization—40 million miles from Earth."

## Terraforming



An artist's conception of a terraformed Mars (2009)

It may be possible to terraform Mars to allow a wide variety of living things, including humans, to survive unaided on Mars' surface.

### ***Radiation***

Mars has no global magnetic field comparable to Earth's geomagnetic field. Combined with a thin atmosphere, this permits a significant amount of ionizing radiation to reach the Martian surface. The Mars Odyssey spacecraft carried an instrument, the Mars Radiation Environment Experiment (MARIE), to measure the dangers to humans. MARIE found that radiation levels in orbit above Mars are 2.5 times higher than at the International Space Station. Average doses were about 22 millirads per day (220

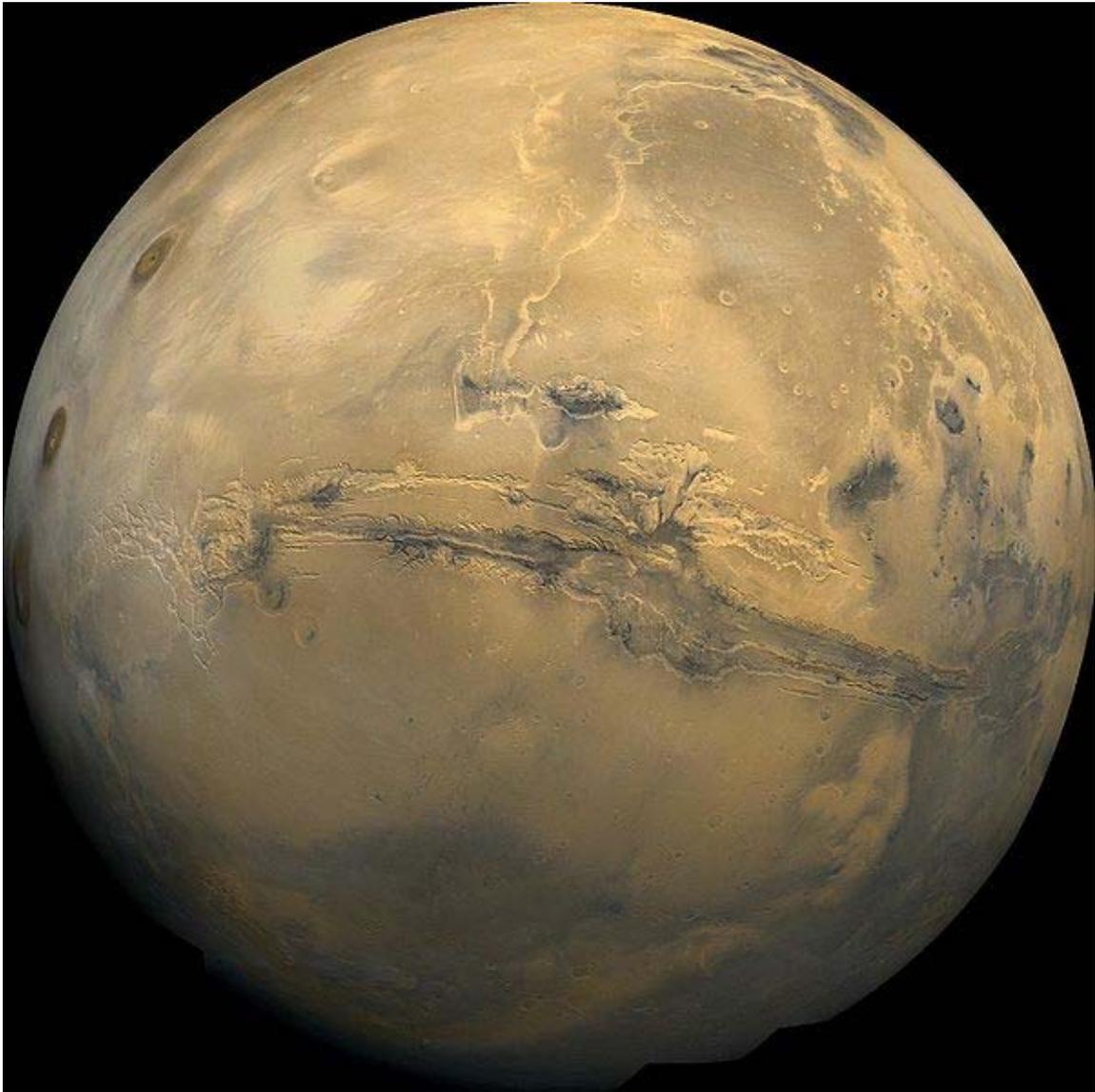
micrograys per day or 0.08 gray per year.) A three year exposure to such levels would be close to the safety limits currently adopted by NASA. Levels at the Martian surface would be somewhat lower and might vary significantly at different locations depending on altitude and local magnetic fields.

Occasional solar proton events (SPEs) produce much higher doses. Some SPEs were observed by MARIE that were not seen by sensors near Earth due to the fact that SPEs are directional, making it difficult to warn astronauts on Mars early enough.

Much remains to be learned about space radiation. In 2003, NASA's Lyndon B. Johnson Space Center opened a facility, the NASA Space Radiation Laboratory, at Brookhaven National Laboratory that employs particle accelerators to simulate space radiation. The facility will study its effects on living organisms along with shielding techniques. There is some evidence that this kind of low level, chronic radiation is not quite as dangerous as once thought; and that radiation hormesis occurs. The consensus among those that have studied the issues is that radiation levels, with the exception of the SPEs, that would be experienced on the surface of Mars, and while journeying there, are certainly a concern, but are not thought to prevent a trip from being made with current technology.

## ***Transportation***

### **Interplanetary spaceflight**



Mars (Viking 1, 1980)

Mars requires less energy per unit mass ( $\Delta V$ ) to reach from Earth than any planet except Venus. Using a Hohmann transfer orbit, a trip to Mars requires approximately nine months in space. Modified transfer trajectories that cut the travel time down to seven or six months in space are possible with incrementally higher amounts of energy and fuel compared to a Hohmann transfer orbit, and are in standard use for robotic Mars missions. Shortening the travel time below about six months requires higher  $\Delta v$  and an exponentially increasing amount of fuel, and is not feasible with chemical rockets, but would be perfectly feasible with advanced spacecraft propulsion technologies, some of which have already been tested, such as VASIMR, and nuclear rockets, in the formers

case, a trip time of forty days could be attainable, and in the latter, a trip time down to about two weeks. Another possibility is constant-acceleration technologies such as space proven solar sails and ion drives which permits passage times at close approaches on the order of several weeks. Both of these propulsion systems have been deployed and could readily obtain a constant acceleration of 0.1g.

During the journey the astronauts are subject to radiation, which requires a means to protect them. Cosmic radiation and solar wind cause DNA damage, which increases the risk of cancer significantly. The effect of long term space travel in the interplanetary space is unknown, but scientists estimate up to 19% probability for male persons to die of cancer because of the radiation during the journey to Mars and back to Earth. Together with the base probability of 20% for a male person on Earth to die from cancer this gives a probability of 39%. For women the probability is even higher due to their larger glandular tissues.

## **Landing on Mars**

Mars has a gravity 0.38 times that of the Earth and the density of its atmosphere is 1% of that on Earth. The relatively strong gravity and the presence of aerodynamic effects makes it difficult to land heavy, crewed spacecraft with thrusters only as was done with the Apollo moon landings, yet the atmosphere is too thin for aerodynamic effects to be of much help in braking and landing a large vehicle. Landing piloted missions on Mars will require braking and landing systems different from anything used to land crewed spacecraft on the Moon or robotic missions on Mars.

If one assumes carbon nanotube construction material will be available with a strength of 130 GPa then a space elevator could be built to land men and material on Mars. A space elevator on Phobos has also been proposed.

## **Communication**

Communications with Earth are relatively straightforward during the half-sol when the Earth is above the Martian horizon. NASA and ESA included communications relay equipment in several of the Mars orbiters, so Mars already has communications satellites. While these will eventually wear out, additional orbiters with communication relay capability are likely to be launched before any colonization expeditions are mounted.

The one-way communication delay due to the speed of light ranges from about 3 minutes at closest approach (approximated by perihelion of Mars minus aphelion of Earth) to 22 minutes at the largest possible superior conjunction (approximated by aphelion of Mars plus aphelion of Earth). Telephone conversations or Internet Relay Chat between Earth and Mars would be highly impractical due to the long time lags involved. NASA has found that direct communication can be blocked for about two weeks every synodic period, around the time of superior conjunction when the Sun is directly between Mars and Earth, although the actual duration of the communications blackout varies from mission to mission depending on various factors - such as the amount of link margin

designed into the communications system, and the minimum data rate that is acceptable from a mission standpoint. In reality most missions at Mars have had communications blackout periods of the order of a month.

A satellite at either of the Earth-Sun  $L_4/L_5$  Lagrange points could serve as a relay during this period to solve the problem; even a constellation of communications satellites would be a minor expense in the context of a full colonization program. However the size and power of the equipment needed for these distances make the  $L_4$  and  $L_5$  locations unrealistic for relay stations, and the inherent stability of these regions, while beneficial in terms of station-keeping, also attracts asteroids, which could pose a severe risk to any satellite.

Recent work by the University of Strathclyde's Advanced Space Concepts Laboratory, in collaboration with the European Space Agency, has suggested an alternative relay architecture based on highly non-Keplerian orbits. These are a special kind of orbit produced when continuous low-thrust propulsion, such as that produced from an ion engine or solar sail, modifies the natural trajectory of a spacecraft. Such an orbit would enable continuous communications during solar conjunction by allowing a relay spacecraft to "hover" above Mars, out of the orbital plane of the two planets. Such a relay avoids the problems of satellites stationed at either  $L_4$  or  $L_5$  by being significantly closer to the surface of Mars while still maintaining continuous communication between the two planets.

### ***Robotic precursors***

The path to a human colony could be prepared by robotic systems such as the Mars Exploration Rovers *Spirit* and *Opportunity*. These systems could help locate resources, such as ground water or ice, that would help a colony grow and thrive. The lifetimes of these systems would be measured in years and even decades, and as recent developments in commercial spaceflight have shown, it may be that these systems will involve private as well as government ownership. These robotic systems also have a reduced cost compared with early crewed operations, and have less political risk.

Wired systems might lay the groundwork for early crewed landings and bases, by producing various consumables including fuel, oxidizers, water, and construction materials. Establishing power, communications, shelter, heating, and manufacturing basics can begin with robotic systems, if only as a prelude to crewed operations.

### ***Early human missions***

Early human missions to Mars, such as those being tentatively planned by NASA, FKA and ESA would not be direct precursors to colonization. They are intended solely as exploration missions, as the *Apollo* missions to the Moon were not planned to be sites of a permanent base.

Colonization requires the establishment of permanent bases that have potential for self-expansion. A famous proposal for building such bases is the Mars Direct plan, advocated by Robert Zubrin. The Mars Society has established the Mars Analogue Research Station Programme at sites Devon Island in Canada and in Utah, United States, to experiment with different plans for human operations on Mars, based on Mars Direct. Modern Martian architecture concepts often include facilities to produce oxygen and propellant on the surface of the planet.

## ***Economics***

As with early colonies in the New World, economics would be a crucial aspect to a colony's success. The reduced gravity well of Mars and its position in the solar system may facilitate Mars-Earth trade and provide the rationalization for continued settlement of the planet.

Mars' reduced gravity together with its rotation rate makes it possible for the construction of a space elevator with today's materials, although the low orbit of Phobos could present engineering challenges. If constructed, the elevator could transport minerals and other natural resources extracted from the planet.

A major economic problem is the enormous up-front investment required to establish the colony and perhaps also terraform the planet.

Some early Mars colonies might specialize in developing local resources for Martian consumption, such as water and/or ice.

Another main inter-Martian trade good during early colonization could be manure. Assuming that life doesn't exist on Mars, the soil is going to be very poor for growing plants, so manure and other fertilizers will be valued highly in any Martian civilization until the planet changes enough chemically to support growing vegetation on its own.

Solar power is a candidate for power for a Martian colony. Solar insolation (the amount of solar radiation that reaches Mars) is about 42% of that on Earth, since Mars is about 52% farther from the Sun and insolation falls off as the square of distance. But the thin atmosphere would allow almost all of that energy to reach the surface as compared to Earth, where the atmosphere absorbs roughly a quarter of the solar radiation.

Nuclear power is also a good candidate, since the fuel is very dense for cheap transportation from Earth. Nuclear power also produces heat, which would be extremely valuable to a Mars colony.

Heating requirements could be lowered if the colonists use domes to trap solar heat, especially for greenhouses.

## ***Possible locations for colonies***

Mars can be considered in broad regions for discussion of possible colony sites.

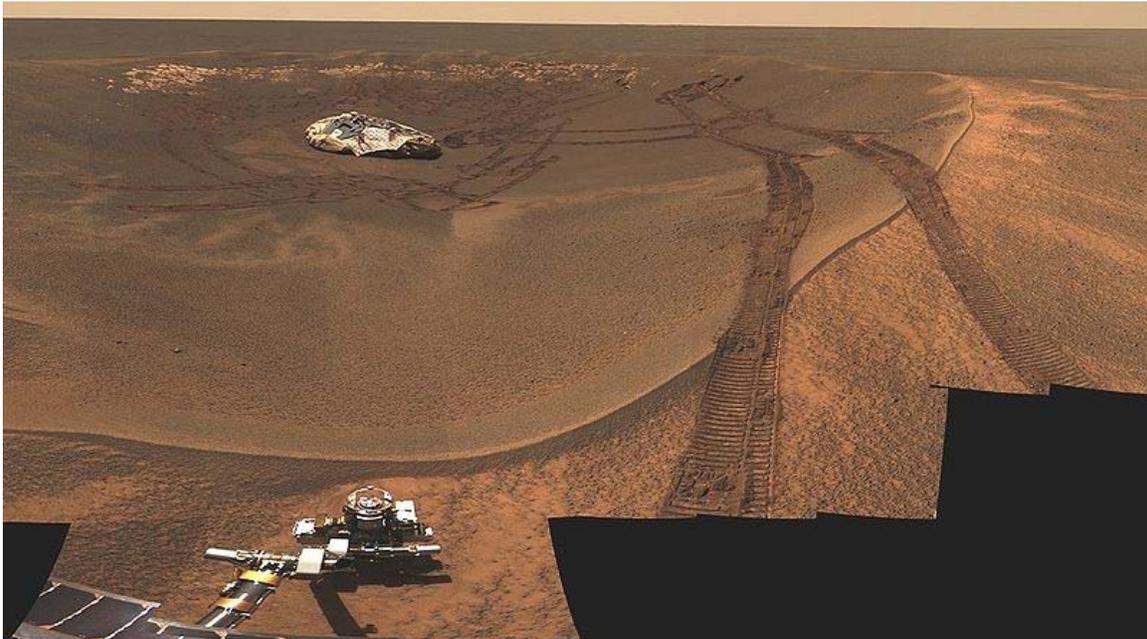
### **Polar regions**

Mars' north and south poles once attracted great interest as colony sites because seasonally-varying polar ice caps have long been observed by telescope from Earth. Mars Odyssey found the largest concentration of water near the north pole, but also showed that water likely exists in lower latitudes as well, making the poles less compelling as a colony locale. Like Earth, Mars sees a midnight sun at the poles during local summer and polar night during local winter.

### **Equatorial regions**

Mars Odyssey found what appear to be natural caves near the volcano Arsia Mons. It has been speculated that colonists could benefit from the shelter that these or similar structures could provide from radiation and micrometeoroids. Geothermal energy is also suspected in the equatorial regions.

### **Midlands**



Eagle Crater, as seen from *Opportunity* (2004)

The exploration of Mars' surface is still underway. The two Mars Exploration Rovers, *Spirit* and *Opportunity*, have encountered very different soil and rock characteristics. This suggests that the Martian landscape is quite varied and the ideal location for a colony

would be better determined when more data becomes available. As on Earth, seasonal variations in climate become greater with distance from the equator.

## **Valles Marineris**

Valles Marineris, the "Grand Canyon" of Mars, is over 3,000 km long and averages 8 km deep. Atmospheric pressure at the bottom would be some 25% higher than the surface average, 0.9 kPa vs 0.7 kPa. The canyon runs roughly east-west, so shadows from its walls should not interfere too badly with solar power collection. River channels lead to the canyon, indicating it was once flooded.

## **Lava Tubes**

Several lava tube skylights on Mars have been located. Earth based examples indicate that some should have lengthy passages offering complete protection from radiation and be relatively easy to seal using on site materials, especially in small subsections.

## **Advocacy**

Making Mars colonization a reality is advocated by several groups with different reasons and proposals. One of the oldest is the Mars Society. They promote a NASA program to accomplish human exploration of Mars and have set up Mars analog research stations in Canada and the United States. Another group is Marsdrive, which is dedicated to private initiatives for the exploration and settlement of Mars.

## **Concerns**

Besides the general criticism of human colonization of space, there are specific concerns about a colony on Mars:

- Mars has a gravity 0.38 times that of the Earth and a density of the atmosphere of 1% that on Earth. The stronger gravity than the Moon and the presence of aerodynamic effects makes it more difficult to land heavy, crewed spacecraft with thrusters only, yet the atmosphere is also too thin to get very much use out of aerodynamic effects for braking and landing. Landing piloted missions on Mars will require a braking and landing system different from anything used to land crewed spacecraft on the Moon or robotic missions on Mars.
- The question of whether life once existed or exists now on Mars has not been settled, raising concerns about possible contamination of the planet with Earth life.
- Advocates of a return to the Moon say the Moon is a more logical first location for a first planetary colony, perhaps using it as practice for future manned missions to Mars. However, in several ways experience gained on the moon would not be applicable to the task of colonizing Mars. The moon has no

atmosphere, no analogous geology and a much greater temperature range and rotational period. These differences make Mars more in common with Earth than the Moon. Antarctica or desert areas of Earth provide much better training grounds at vastly lesser cost. Also, the Moon is extremely poor in several of the key elements required for life, most notably hydrogen, nitrogen and carbon (50 – 100 ppm), and has only 47.2% of the delta-v requirement for launching to orbit that Mars has.

- It is unknown whether Martian gravity can support human life in the long term (all experience is at either  $\sim 1g$  or zero gravity). Space medicine researchers have theorized on whether the health benefits of gravity rise slowly or quickly between weightlessness and full Earth gravity. One theory is that sleeping chambers built inside centrifuges would minimize the health problems. The Mars Gravity Biosatellite experiment was due to become the first experiment testing the effects of partial gravity, artificially generated at 0.38 g to match Mars gravity, on mammal life, specifically on mice, throughout the life cycle from conception to death. However, in 2009 the Biosatellite project was cancelled due to lack of funds.
- Mars' escape velocity is 5 km/s, which, though less than half that for Earth, is reasonably high compared to the Moon's 2.38 km/s or the negligible escape velocity of most asteroids. This could make physical export trade from Mars to other planets and habitats less viable economically.
- There is likely to be little economic return from the colonization of Mars while Lunar and Near Earth Asteroid industry is likely to be exporting to Earth.
- Mars has dust storms which can reduce solar power. The largest of these storms can cover much of the planet.

## Chapter-12

# Mars to Stay

**Mars to Stay** is the proposal that astronauts sent to Mars for the first time should stay there indefinitely, both to reduce mission cost and to ensure permanent settlement of Mars. Among many other notable Mars to Stay advocates, former Apollo astronaut Buzz Aldrin has been particularly outspoken, suggesting in numerous forums "Forget the Moon, Let's Head to Mars!" The Mars Underground, Mars Homestead Foundation, and Mars Artists Community have also adopted Mars to Stay policy initiatives. The earliest formal outline of a Mars to Stay mission architecture was given at the Case for Mars VI Workshop in 1990, during a presentation by George Herbert titled "One Way to Mars."



Concept for NASA Design Reference Mission Architecture 5.0 (2009)

### ***Proposals***

#### ***Original Aldrin Plan***

Under a Mars to Stay mission architecture the first humans to travel to Mars would be composed of a six-person team. After this initial landing subsequent missions over five years will raise the number of persons on the Martian surface to 30, thereby beginning an organically evolving Martian settlement. Since the Martian surface offers all the natural

resources and elements necessary to sustain human society—unlike, for example the moon—a permanent Martian settlement is thought to be the most effective way to ensure humankind becomes a space-faring, multi-planet species. Through the use of digital fabricators and in vitro fertilization it is assumed a permanent human settlement on Mars can grow organically from an original thirty to forty pioneers.

A Mars exploration program following Aldrin's Mars to Stay initiative would enlist astronauts in the following timeline:

- Age 30: an offer to help settle Mars is extended to select pioneers
- Age 30-35: training and social conditioning for long-duration isolation and time-delay communications
- Age 35: launch three married couples to Mars; followed in subsequent years by a dozen or more couples
- Age 35-65: development of sheltered underground living spaces; artificial insemination ensures genetic diversity
- Age 65: an offer to return to Earth or retire on Mars is given to first generation settlers

As Aldrin has said, "...who knows what advances will have taken place. The first generation can retire there, or maybe we can bring them back."

### ***"Hundred Year Starship Initiative"***

On October 2010 NASA Ames Research Center Director Pete Worden introduced the Hundred Year Starship initiative, a project to embark on a one-way mission from Earth to Mars by 2030. The astronauts would be sent supplies from Earth on a regular basis. The mission is planned to take place no earlier than 2030. Controversy immediately arose over the name of the enterprise, given that Mars settlement could have begun within five years of the announcement -- rather than portrayed as an exotic "100 year" fantasy.

### ***"To Boldly Go: A One-Way Human Mission to Mars," Journal of Cosmology***

The October-November, 2010, Journal of Cosmology reprinted an article by Dirk Schulze-Makuch (Washington State University) and Paul Davies (Arizona State University) from the book "The Human Mission to Mars. Colonizing the Red Planet." Highlights of their mission plan are:

- No base on the Moon is needed. Given the broad variety of resources available on Mars, the long-term survival of Martian settlers is much more feasible than Lunar settlers.
- Since Mars affords neither an ozone shield nor magnetospheric protection, robots would prepare a basic modular base inside near-surface lava tubes and ice caves for the human settlers.

- A volunteer signing up for a one-way mission to Mars would do so with the full understanding that he or she will not return to Earth; Mars exploration would proceed for a long time on the basis of outbound journeys only.
- The first human contingent would consist of a crew of four, ideally (if budget permits) distributed between two two-man spacecraft for mission redundancy.
- Over time humans on Mars will increase with follow-up missions. Several subsurface biospheres would be created until there were 150+ individuals in a viable gene pool. Genetic engineering would further contribute to the health and longevity of settlers.

### ***Initial and permanent settlement***

Initial explorers leave equipment in orbit and at landing zones scattered considerable distances from the main settlement. Subsequent missions therefore are assumed to become easier and safer to undertake, with the likelihood of back-up equipment being present if accidents in transit or landing occur.

Large subsurface, pressurized habitats would be the first step toward human settlement; as Dr. Robert Zubrin suggests in the first chapter of his book *Mars Direct* these structures can be built as Roman-style atria in mountainsides or underground with easily produced Martian brick. During and after this initial phase of habitat construction, hard-plastic radiation- and abrasion-resistant geodesic domes could be deployed on the surface for eventual habitation and crop growth. Nascent industry would begin using indigenous resources: the manufacture of plastics, ceramics and glass could be easily achieved.

The longer-term work of terraforming Mars requires an initial phase of global warming to release atmosphere from the Martian regolith and to create a water-cycle. There would be no cost issue associated to terraforming as it would be in the best interest of settlers to make sure that their daily activities positively influence the improvement of the environment. Three methods of global warming are described by Zubrin, who suggests they are best deployed in tandem: orbital mirrors to heat the surface; factories on the ground to pump halocarbons into the atmosphere; and the seeding of bacteria which can metabolize water, nitrogen and carbon to produce ammonia and methane (these gases would aid in global warming). While the work of terraforming Mars is on-going, robust settlement of Mars can continue.

*The Case for Mars* acknowledges any Martian colony will be partially Earth-dependent for centuries. However, Zubrin suggests Mars may be profitable for two reasons. First, it may contain concentrated supplies of metals equal to or of greater value than silver, which have not been subjected to millennia of human scavenging; it is suggested such ores may be sold on Earth for profit. Secondly, the concentration of deuterium—an extremely expensive but essential fuel for the nuclear power industry—is five times greater on Mars. Humans emigrating to Mars, under this paradigm, thus have an assured industry; it is assumed the planet will be a magnet for settlers as wage costs will be high. Because of the labor shortage on Mars and its subsequent high pay-scale, Martian

civilization and the value placed upon each individual's productivity is proposed as a future engine of both technological and social advancement.”

## **Risks**



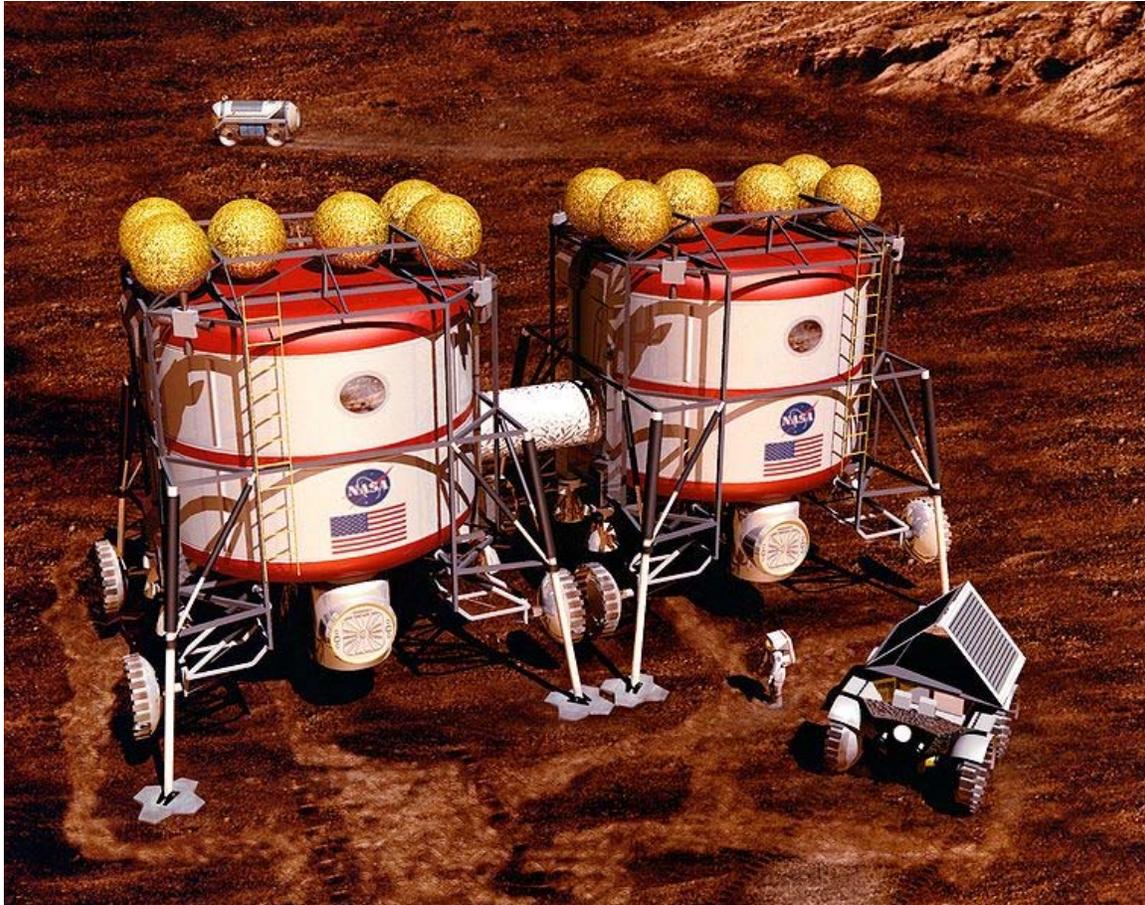
Artist's conception of a human mission on Mars  
1989 painting by Les Bossinas of Lewis Research Center for NASA

In the fifth chapter of "Mars Direct", Zubrin dismisses the idea that radiation and zero-gravity are unduly hazardous. He claims that cancer rates *do* increase for astronauts who have spent extensive time in space, but only marginally. Similarly, while zero-gravity presents challenges, near total recovery of musculature and immune system vitality is assumed once on the Martian surface. Back-contamination — humans acquiring and spreading Martian viruses — is described as "just plain nuts", because there are no host organisms on Mars for disease organisms to have evolved.

In the same chapter, Zubrin decisively denounces and rejects suggestions that the Moon should be used as waypoint to Mars or as a preliminary training area. "It is ultimately much easier to journey to Mars from low Earth orbit than from the moon and using the latter as a staging point is a pointless diversion of resources." While the Moon may superficially appear a good place to perfect Mars exploration and habitation techniques, the two bodies are radically different. The moon has no atmosphere, no analogous geology and a much greater temperature range and rotational period of illumination. It is argued Antarctica, desert areas of Earth, and precisely controlled chilled vacuum

chambers on easily accessible NASA centers on Earth provide much better training grounds at lesser cost.

### ***Public reception***



Artist's conception of a Mars Habitat  
1993 by John Frassanito and Associates for NASA

"Should the United States space program send a mission to Mars, those astronauts should be prepared to stay there," said Lunar astronaut Buzz Aldrin during a high-profile, widely reported interview on "Mars to Stay" initiatives. The time and expense required to send astronauts to Mars, argues Aldrin, "warrants more than a brief sojourn, so those who are on board should think of themselves as pioneers. Like the Pilgrims who came to the New World or the families who headed to the Wild West, they should not plan on coming back home." While the Moon is a shorter trip of two or three days, according to Mars advocates, it offers virtually no potential for independent settlements. Studies have found that Mars, on the other hand, has vast reserves of frozen water, all of the basic elements, and more closely mimics both gravitational and illumination conditions on Earth. "It is easier to subsist, to provide the support needed for people there than on the Moon." In an interview with reporters, the second man to set foot on the Moon said the Red Planet offered far greater potential than Earth's satellite as a place for habitation.

"If we are going to put a few people down there and ensure their appropriate safety, would you then go through all that trouble and then bring them back immediately, after a year, a year and a half?" Aldrin asks. "They need to go there more with the psychology of knowing that you are a pioneering settler and you don't look forward to go back home again after a couple of years," he said.

The most comprehensive statement of a rationale for "Mars to Stay" was laid out by Dr. Aldrin in a May 2009 Popular Mechanics article, as follows:

"The agency's current Vision for Space Exploration will waste decades and hundreds of billions of dollars trying to reach the moon by 2020—a glorified rehash of what we did 40 years ago. Instead of a steppingstone to Mars, NASA's current lunar plan is a detour. It will derail our Mars effort, siphoning off money and engineering talent for the next two decades. If we aspire to a long-term human presence on Mars—and I believe that should be our overarching goal for the foreseeable future—we must drastically change our focus. Our purely exploratory efforts should aim higher than a place we've already set foot on six times. In recent years my philosophy on colonizing Mars has evolved. I now believe that human visitors to the Red Planet should commit to staying there permanently. One-way tickets to Mars will make the missions technically easier and less expensive and get us there sooner. More importantly, they will ensure that our Martian outpost steadily grows as more homesteaders arrive. Instead of explorers, one-way Mars travelers will be 21st-century pilgrims, pioneering a new way of life. It will take a special kind of person. Instead of the traditional pilot/ scientist/engineer, Martian homesteaders will be selected more for their personalities—flexible, inventive and determined in the face of unpredictability. In short, survivors."

The Mars Artists Community has adopted Mars to Stay as their primary policy initiative. During a 2009 public hearing of the U.S. Human Space Flight Plans Committee at which Dr. Robert Zubrin presented a summary of the arguments in book *The Case for Mars*, dozens of placards reading "Mars Direct Cowards Return to the Moon" were placed throughout the Carnegie Institute. The passionate uproar among space exploration advocates - both favorable and critical - resulted in the Mars Artists Community creating several dozen more designs, with such slogans as, "Traitors Return to Earth" and "What Would Zheng He Do?"

In October 2009, Eric Berger of the Houston Chronicle wrote of 'Mars to Stay' as perhaps the only program which can revitalize America's space program:

"What if NASA could land astronauts on Mars in a decade, for not ridiculously more money than the \$10 billion the agency spends annually on human spaceflight? It's possible, say some space buffs, although there's a catch. The astronauts we'd send would never come home. Relieving NASA of the need to send fuel and rocketry to blast humans off the Martian surface, which has slightly more than twice the gravity of the moon, would actually reduce costs by about a factor of 10, by some estimates."

Hard Science Fiction writer Mike Brotherton has found "Mars to Stay" appealing for both economic and safety reasons, but more emphatically, as a fulfillment of the ultimate mandate by which "our manned space program is sold, at least philosophically and long-term, as a step to colonizing other worlds." Two thirds of the respondents to a poll on his website expressed interest in a one-way ticket to Mars "if mission parameters are well-defined" (not suicidal).

In June 2010 Buzz Aldrin gave an interview to Vanity Fair in which he restated Mars to Stay:

"Did the Pilgrims on the Mayflower sit around Plymouth Rock waiting for a return trip? They came here to settle. And that's what we should be doing on Mars. When you go to Mars, you need to have made the decision that you're there permanently. The more people we have there, the more it can become a sustaining environment. Except for very rare exceptions, the people who go to Mars shouldn't be coming back. Once you get on the surface, you're there."

The October-November, 2010, Journal of Cosmology reprinted an article by Dirk Schulze-Makuch (Washington State University) and Paul Davies (Arizona State University) from the book "The Human Mission to Mars. Colonizing the Red Planet." The following summarizes their rationale for Mars to Stay:

"A human mission to Mars is technologically feasible, but hugely expensive requiring enormous financial and political commitments. A creative solution to this dilemma would be a one-way human mission to Mars in place of the manned return mission that remains stuck on the drawing board. Our proposal would cut the costs several fold but ensure at the same time a continuous commitment to the exploration of Mars in particular and space in general. It would also obviate the need for years of rehabilitation for returning astronauts, which would not be an issue if the astronauts were to remain in the low-gravity environment of Mars. We envision that Mars exploration would begin and proceed for a long time on the basis of outbound journeys only."

### ***"New York Times" op-eds***

"Mars to Stay" has been explicitly proposed by two op-ed pieces in the "New York Times".

#### **"A One-Way Ticket to Mars" Krauss, Lawrence. New York Times Op-Ed, Sept 1, 2009:"**

Following a similar line of argument to Buzz Aldrin, Lawrence Krauss asks in an Op-Ed, "Why are we so interested in bringing the Mars astronauts home again?". While the idea of sending astronauts aloft never to return may be jarring upon first hearing, the rationale for one-way exploration and settlement trips has both historical and practical roots. For example, colonists and pilgrims seldom set off to the New World with the expectation of

a return trip. As Lawrence Krauss writes, "To boldly go where no one has gone before does not require coming home again."

Dr. Krauss modifies the standard "Mars to Stay" architecture by "restricting the voyage to older astronauts, whose longevity is limited. Here again, I have found a significant fraction of scientists older than 65 who would be willing to live out their remaining years on the red planet or elsewhere." This initial first generation of elderly astronauts would accept higher radiation doses while building eventual subsurface habitats, presumably, because the effects of increased radiation would not affect them during the remainder of their lives.

"If it sounds unrealistic to suggest that astronauts would be willing to leave home never to return alive, then consider the results of several informal surveys I and several colleagues have conducted recently. One of my peers in Arizona recently accompanied a group of scientists and engineers from the Jet Propulsion Laboratory on a geological field trip. During the day, he asked how many would be willing to go on a one-way mission into space. Every member of the group raised his hand." Krauss, Lawrence. New York Times Op-Ed "A One-Way Ticket to Mars"

Additional immediate and pragmatic reasons to consider one-way human space exploration missions are explored by Krauss. Since much of the cost of a voyage to Mars will be spent on coming home again, if the fuel for the return is carried onboard, this greatly increases the mission mass requirement - which in turn requires even more fuel. "Human space travel is so expensive and so dangerous" according to Krauss, "we are going to need novel, even extreme solutions if we really want to expand the range of human civilization beyond our own planet." Delivering food and supplies to pioneers via unmanned spacecraft is less expensive than designing an immediate return trip.

**"Life (and Death) on Mars," Davies, Paul. New York Times Op-Ed, January 15, 2004:"**

In an earlier 2004 Op-Ed for the New York Times, Paul Davies motivation for the less expensive, permanent "one-way to stay option" arises from a theme common in "Mars to Stay" advocacy: "Mars is one of the few accessible places beyond Earth that could have sustained life [...and] alone among our sister planets, it is able to support a permanent human presence."

"Why is going to Mars so expensive? Mainly it's the distance from Earth. At its closest point in orbit, Mars lies 35 million miles away from us, necessitating a journey of many months, whereas reaching the Moon requires just a few days' flight. On top of this, Mars has a surface gravity that, though only 38 percent of Earth's, is much greater than the Moon's. It takes a lot of fuel to blast off Mars and get back home. If the propellant has to be transported there from Earth, costs of a launching soar. Without some radical improvements in technology, the prospects for sending astronauts on a round-trip to Mars any time soon are slim, whatever the presidential rhetoric. What's more, the president's suggestion of using the Moon as a base — a place to assemble equipment and produce

fuel for a Mars mission less expensively — has the potential to turn into a costly sideshow. There is, however, an obvious way to slash the costs and bring Mars within reach of early manned exploration. The answer lies with a one-way mission."

Under Davies' plan an initial colony of four astronauts equipped with a small nuclear reactor and a couple of rover vehicles would make their own oxygen, grow food, and even initiate building projects using local raw materials. Supplemented by food shipments, medical supplies, and replacement gadgets from Earth, the colony would be indefinitely sustained. Davies argues that since, "some people gleefully dice with death in the name of sport or adventure [and since] dangerous occupations that reduce life expectancy through exposure to hazardous conditions or substances are commonplace," we ought to not find the risks involved in a Mars to Stay architecture unusual.

"A century ago, explorers set out to trek across Antarctica in the full knowledge that they could die in the process, and that even if they succeeded their health might be irreversibly harmed. Yet governments and scientific societies were willing sponsors of these enterprises." Asks Davies, "Why should it be different today?"

## Chapter-13

# Colonization of Mercury



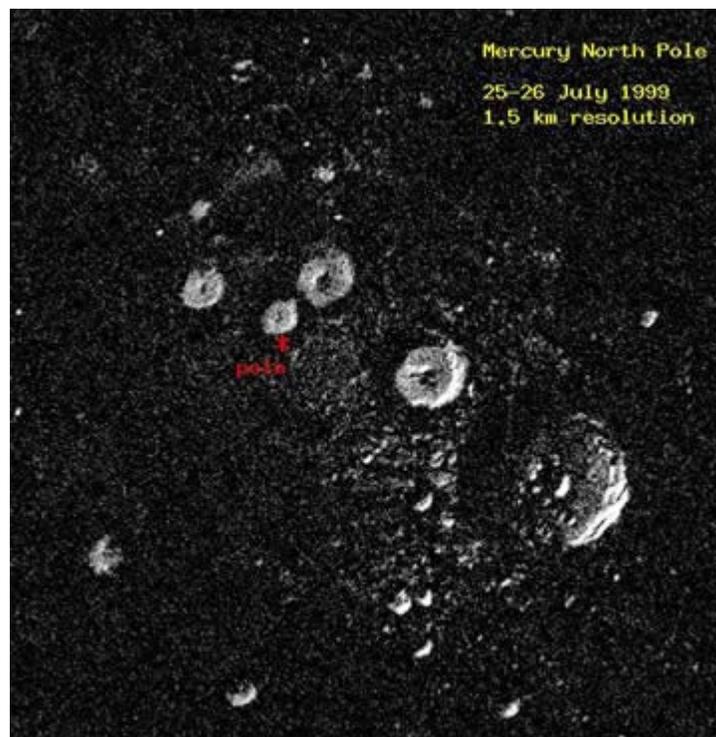
Mercury

Mercury has been suggested as one possible target for space colonization of the inner solar system, along with Mars, Venus, the Moon and the asteroid belt. Permanent colonies would almost certainly be restricted to the polar regions due to the extreme daytime temperatures elsewhere on the planet. Excursions to the other parts of the planet would be feasible with appropriate measures, particularly along the very slowly moving terminator, which would approximate polar conditions.

## **Advantages**

### **Similarity to the Moon**

Like the Earth's Moon, Mercury does not have any significant atmosphere. It is close to the Sun and performs slow rotations with a very small tilt of its axis. Because of this similarity any colonization of Mercury might be performed with the same general technology, approach and equipment as a colonization of the Moon. Bruce Murray referred to Mercury as "A Mini-Earth in Moon's Clothing". Unlike the Moon however, Mercury has the additional advantage of a magnetic field protecting it from cosmic rays and solar storms, and a larger surface gravity of about 0.38 g, nearly equal to that of Mars.



Arecibo Observatory S-band radar image of the north polar region of Mercury by J. Harmon, P. Perrilat, and M. Slade. The resolution is 1.5 kilometers (about 1 mile) and the image measures 450 kilometers on a side. The bright features are thought to be ice deposits on permanently shadowed crater floors.

Radar image of Mercury's north pole

## **Ice in polar craters**

Due primarily to its distance from the Sun, the surface of Mercury can reach 700 K (427 °C, 800 °F), hot enough to melt lead. However, temperatures at the polar regions are much colder and there may even be deposits of ice inside permanently shaded craters. The polar areas do not experience the extreme daily variation in temperature seen on more equatorial areas of Mercury's surface.

## **Solar energy**

Being the closest planet to the Sun, Mercury has vast amounts of solar power available. Its solar constant is 9.13 kW/m<sup>2</sup>, 6.5 times that of Earth or the Moon. Because the tilt of its axis of rotation relative to its orbit is so low, approximately 0.01 degrees, there is also the possibility of so-called peaks of eternal light, similar to those of the Moon—high points located at the poles of the planet that are continuously radiated by the Sun. Even if they do not exist, it is possible that they could be constructed artificially.

In 1986, C.R. Pellegrino and J.R. Powell proposed covering Mercury with solar power farms, and transferring some of the resulting energy into a form useful for propulsion for interstellar travel.

## **Valuable resources**

There are predictions that Mercury's soil may contain large amounts of helium-3, which could become an important source of clean nuclear fusion energy on Earth and a driver for the future economy of the solar system. However, Mercury's magnetic field could have prevented helium-3 from reaching the surface.

Mercury is also theorized to have a crust rich in iron and magnesium silicates, with the highest concentrations of many valuable minerals of any surface in the solar system, in highly concentrated ores.

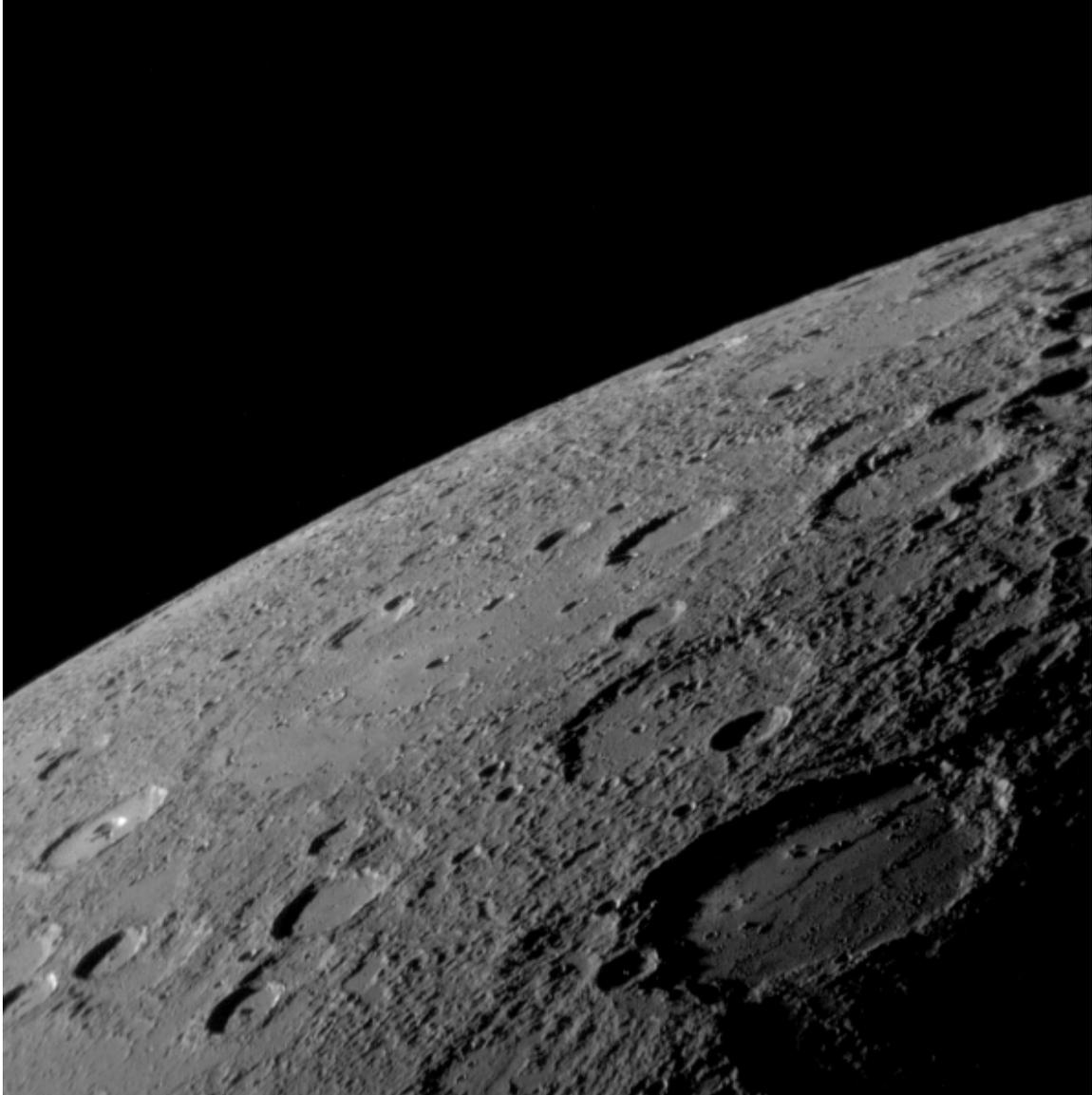
Geologist Stephen Gillett has suggested this will make Mercury an ideal place to build solar sails, which could launch as folded up "chunks" by mass driver from Mercury's surface. Once in space the solar sails would deploy. Since Mercury's solar constant is 6.5 times higher than Earth's, energy for the mass driver should be easy to come by, and solar sails near Mercury would have 6.5 times the thrust they do near Earth. This could make Mercury an ideal place to acquire materials useful in building hardware to send to (and terraform) Venus.

## **Considerable gravity**

Mercury is bigger than the Moon, with a diameter of 4879 km versus 3476 km, and has a higher density due to its large iron core. As a result, gravity on the surface of Mercury is 0.377 g, more than twice that of the Moon (0.1654 g) and very close to the surface gravity on Mars. Since there is evidence of human health problems associated with

extended exposure to low gravity, from this point of view, Mercury might be more attractive for long-term human habitation than the Moon.

### ***Difficulties***



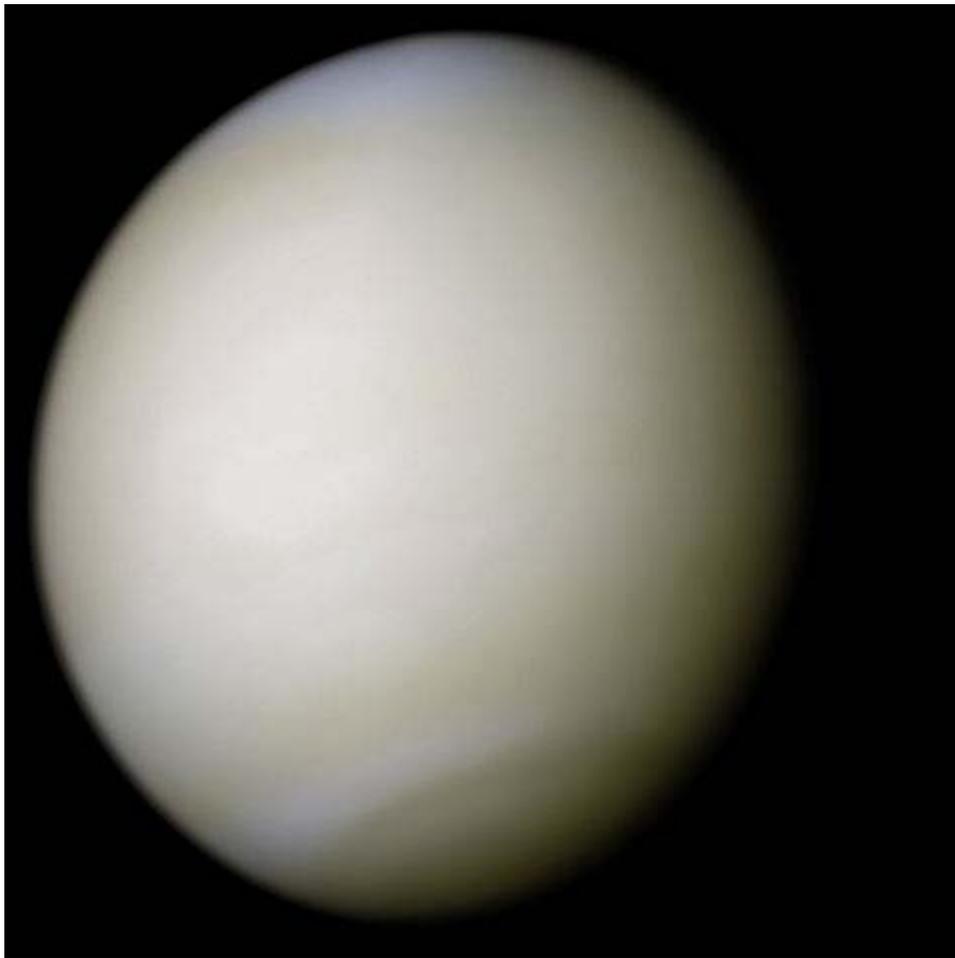
Mercury as imaged by the MESSENGER spacecraft in 2008

The lack of any substantial atmosphere, close proximity to the Sun and long solar days (176 Earth days) would all lead to significant challenges for any future human settlement. A permanent colony would almost certainly be restricted to the polar regions, but temporary excursions toward the equator could take place during the long night. Outside of the possibility of ice at the poles, it is unlikely that the lighter elements needed for life exist on the planet. These would have to be imported.

Mercury is also deep in the Sun's gravitational potential well, requiring a larger velocity change ( $\Delta V$ ) to travel to and from Mercury than is needed for other planets, although, in the past, gravity assist orbits using Venus have been used to reach Mercury. However, entering orbit around Mercury and landing on the surface would take 6 years with current propulsion methods. Solar sails and mass drivers may assist in transportation in the future, but are not viable options at present.

## Chapter-14

# Colonization of Venus



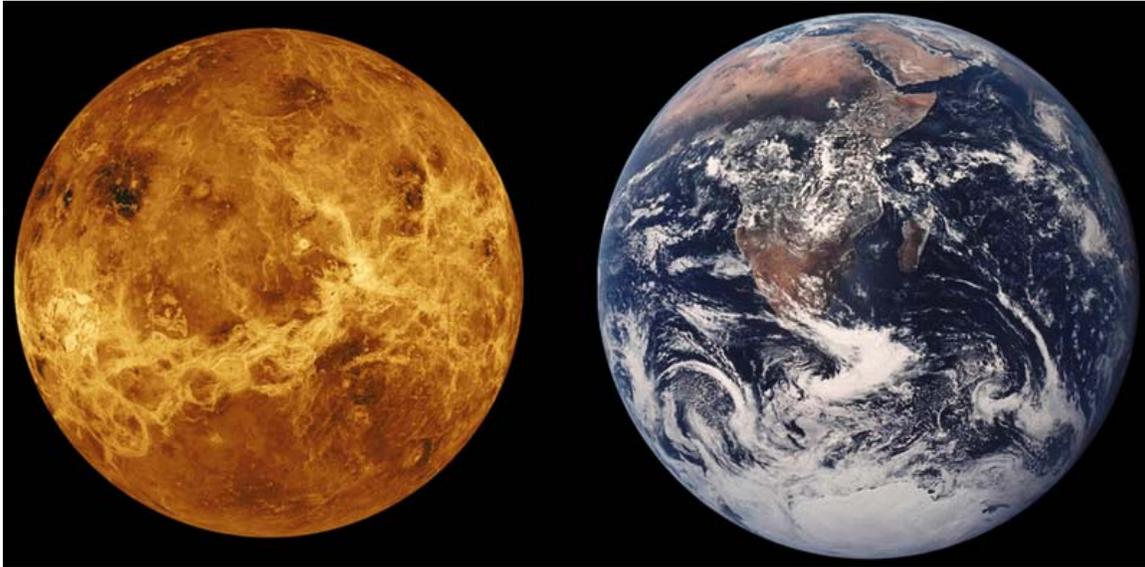
Venus

The **colonization of Venus** has been a subject of much speculation and many works of science fiction since before the dawn of spaceflight, and is still much discussed. With the discovery of Venus' hostile surface environment, attention has largely shifted towards the colonization of the Moon and the colonization of Mars.

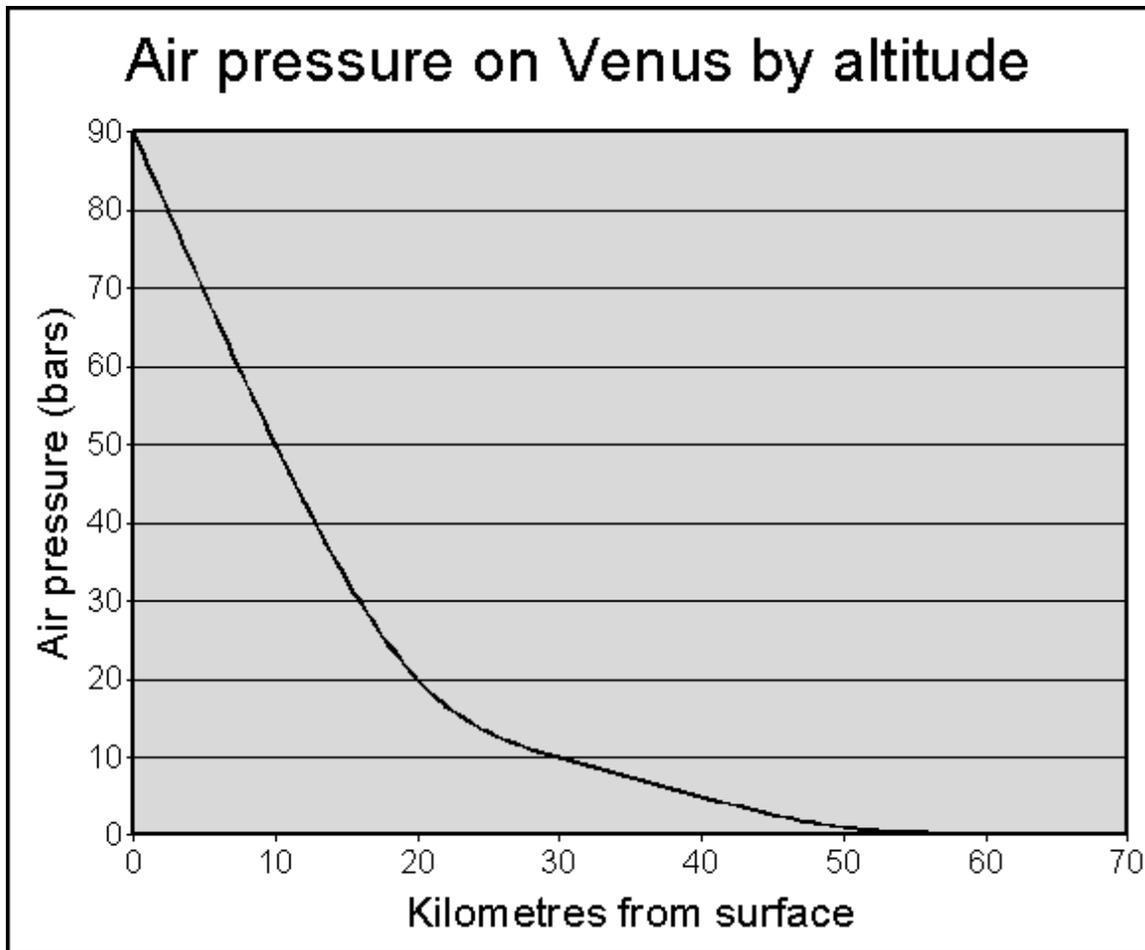
## ***Reasons for colonization***

Space colonization is a step beyond space exploration, and implies the permanent or long-term presence of humans in an environment outside Earth. Colonization of space is arguably the best way to ensure the survival of humans as a species. Other reasons for colonizing space include economic interests, long-term scientific research best carried out by humans, and sheer curiosity. Venus is the second largest terrestrial planet and Earth's closest neighbour, which makes it a potential target.

## ***Advantages***



Scale representations of Venus and the Earth shown next to each other. Venus is only slightly smaller.



Air pressure on Venus, beginning at a pressure on the surface 90 times that of Earth and reaching a single bar by 50 kilometres.

Venus has certain similarities to Earth which might make colonization easier in many respects in comparison with other possible destinations. These similarities, and its proximity, have led Venus to be called Earth's "sister planet".

At present it has not been established whether the gravity of Mars, 0.38 times that of the Earth, would be sufficient to avoid bone decalcification and loss of muscle tone experienced by astronauts living in an environment of microgravity (the probe Mars Gravity Biosatellite was going to be the first probe to investigate this, however it has since been canceled due to lack of funding). In contrast, Venus is close in size and mass to the Earth, resulting in a similar surface gravity (0.904 g). Most other space exploration and colonization plans face concerns about the damaging effect of long-term exposure to fractional g or zero gravity on the human musculoskeletal system. Humans born on Venus would probably have little difficulty adapting to Earth gravity should there be a reason to visit or return; contrasted to return trips from Mars where humans would likely need rehabilitation or the use of an exoskeleton.

Venus's relative proximity makes transportation and communications easier than for most other locations in the solar system. With current propulsion systems, launch windows to Venus occur every 584 days, compared to the 780 days for Mars. Flight time is also somewhat shorter; the probe Venus Express which recently arrived at Venus spent slightly over five months en route, compared to nearly six months for Mars Express. This is because at closest approach, Venus is 45 million km from Earth compared to 56 million km for Mars, making Venus the closest planet to the Earth.

### ***Difficulties***

Venus also presents several significant challenges to human colonization. Surface conditions on Venus are practically impossible to deal with: the temperature at the equator averages around 500 °C (932 °F), higher than the melting point of lead. The atmospheric pressure on the surface is also at least ninety times greater than on Earth, which is equivalent to the pressure experienced under a kilometer of water. These conditions have caused missions to the surface to be extremely brief: the probes Venera 5 and Venera 6 for example were crushed by high pressure whilst still 18 km above the surface. Following landers such as Venera 7 and Venera 8 succeeded in transmitting data after reaching the surface, but these missions were brief as well, surviving no more than a single hour on the surface.

Furthermore, water, in any form, is almost entirely absent from Venus. The atmosphere is devoid of molecular oxygen and is primarily carbon dioxide in poisonously high concentrations. In addition, the visible clouds are composed partly of corrosive sulfuric acid and sulfur dioxide vapor.

### ***Methods of colonization and exploration***

Given the hostile conditions of Venus, a colony on the Venusian surface in its present form is far beyond current technological capabilities.

This has not prevented some science-fiction authors from speculating on ways of overcoming this by, for example, terraforming Venus – making the planet more earth-like. The energy requirements for all terraforming plans are daunting when compared with our current technology, and the time required could possibly span hundreds of years. Other authors speculate that, if a large portion or the entire planet could be shaded, Venus would cool to a useful temperature in mere decades. Such authors postulate methods which would include placing sails (Solar shades) between Venus and the sun at the Lagrange point between the two, controlled dust clouds in space, and a large number of other ideas.

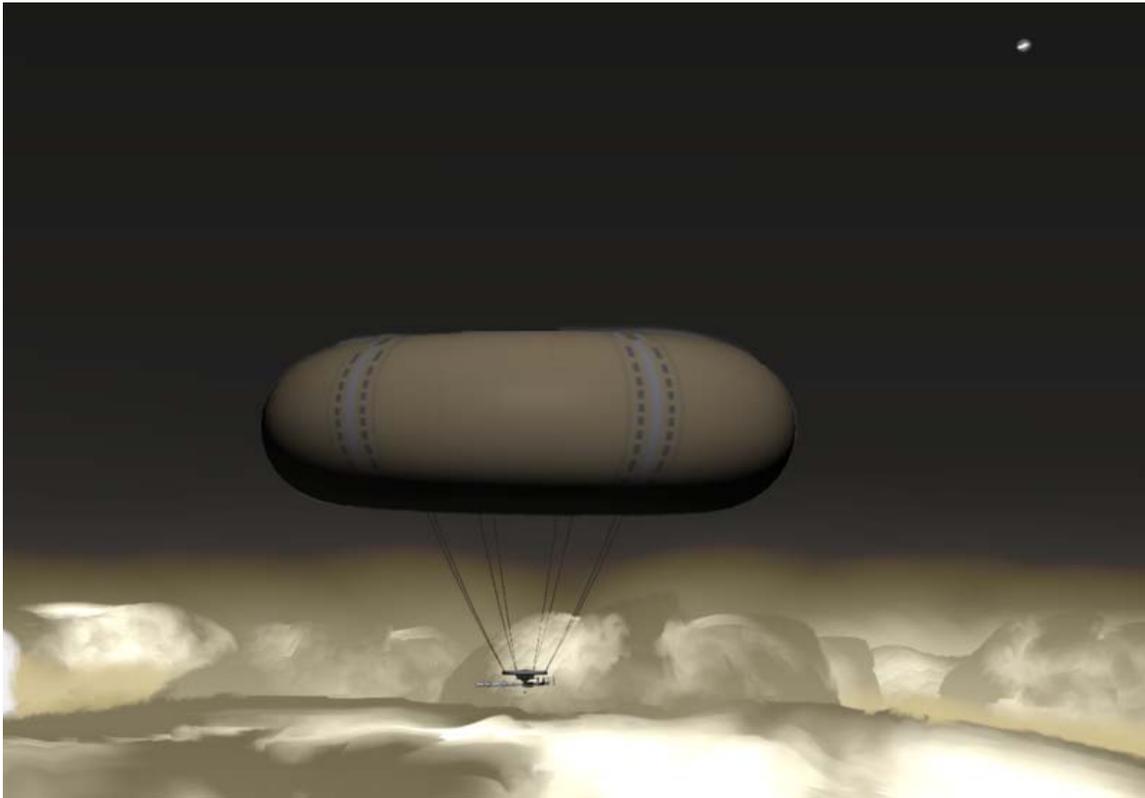
Others suggest a different approach, however, claiming that rather than attempting to colonize Venus' hostile surface, humans might attempt to colonize the Venusian atmosphere (the most habitable known part of any planet outside Earth). This is because at an altitude of approximately 50 kilometers (in Venus's upper atmosphere), the pressure and temperature are Earth-like (1 bar and 0-50 degrees Celsius).

## Exploration and research

As Venus has not been studied as much as objects such as the moon and Mars have, further research would have to be conducted on the planet before a human-powered mission could be approved. The probe Venus Express is currently in orbit around the planet, but other low-cost missions have been proposed to further explore the planet's atmosphere, as the area 50 kilometres above the surface where air pressure is at the same level as Earth has not yet been explored.

It is currently possible to successfully land a robot on the surface. The Soviet Venera program succeeded in doing so – the Venera 13 lander survived for 127 minutes, and the Venera 14 lander for 57 minutes. It is not inconceivable that this survival time could be extended. Improved materials and technology designed to work at the high temperatures and pressures would be necessary. As the survival times of the robotic probes grows longer, enhanced missions might be feasible, including the establishment of a robotic base at locations where important (perhaps fissionable) compounds might be found. The technology for operating under such conditions is at the current time so exotic as to be difficult to conceive, and funding is likely to go elsewhere.

## Aerostat habitats and floating cities



Hypothetical prototype floating outpost studying colonization of Venus around 50 km above the surface supported by a torus full of hydrogen.

Geoffrey A. Landis has summarized the perceived difficulties in colonizing Venus as being merely from the assumption that a colony would need to be based on the surface of a planet:

“However, viewed in a different way, the problem with Venus is merely that the ground level is too far below the one atmosphere level. At cloud-top level, Venus is the paradise planet.”

He has proposed aerostat habitats followed by floating cities, based on the concept that breathable air (21:79 Oxygen-Nitrogen mixture) is a lifting gas in the dense Venusian atmosphere, with over 60% of the lifting power that helium has on Earth. In effect, a balloon full of human-breathable air would sustain itself and extra weight (such as a colony) in midair. At an altitude of 50 km above Venusian surface, the environment is the most Earth-like in the solar system – a pressure of approximately 1 bar and temperatures in the 0°C–50°C range. Because there is not a significant pressure difference between the inside and the outside of the breathable-air balloon, any rips or tears would cause gases to diffuse at normal atmospheric mixing rates, giving time to repair any such damages. In addition, humans would not require pressurized suits when outside, merely air to breathe and a protection from the acidic rain. Alternatively, two-part domes could contain a lifting gas like hydrogen or helium (extractable from the atmosphere) to allow a higher mass density.

Cloud-top colonization also offers a way to avoid the issue of slow Venusian rotation. At the top of the clouds the wind speed on Venus reaches up to 95 m/s (approximately 212 mph), circling the planet approximately every four Earth days in a phenomenon known as "super-rotation". Colonies floating in this region could therefore have a much shorter day length by remaining untethered to the ground and moving with the atmosphere. While a space elevator extending to the surface of Venus is impractical due to the slow rotation, constructing a skyhook that extended into the upper atmosphere and rotated at the wind speed would not be difficult compared to constructing a space elevator on Earth.

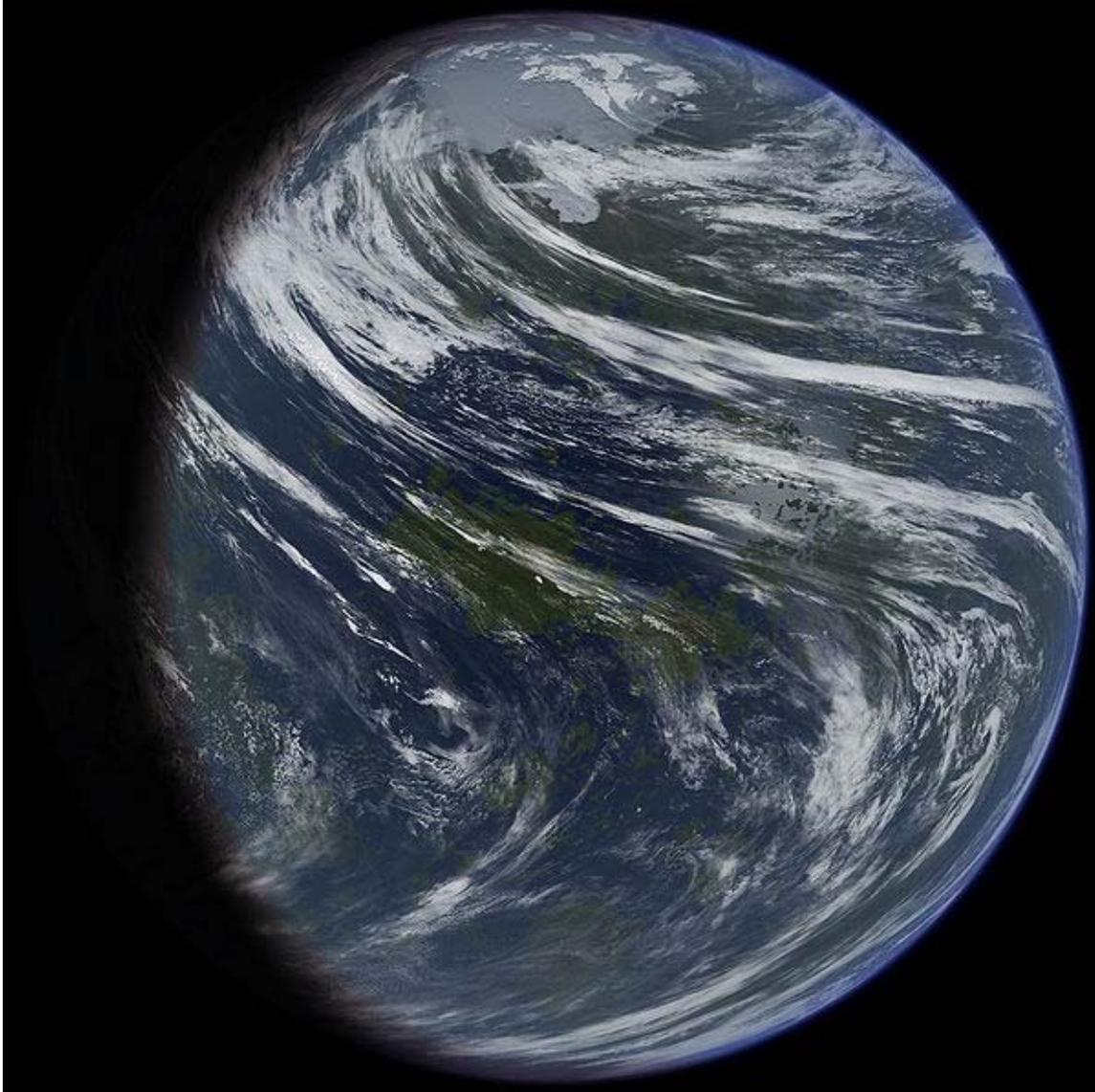
Since such colonies would be viable in current Venusian conditions, this allows a dynamic approach to colonization instead of requiring extensive terraforming measures in advance. The main challenge would be using a substance resistant to sulfuric acid to serve as the structure's outer layer; ceramics or metal sulfates could possibly serve in this role. Dyneema, Polyethylene and Polypropylene would be well usable for the skin of the balloon.

Landis has suggested that as more floating cities were built, they could form a solar shield around the planet, and could simultaneously be used to process the atmosphere into a more desirable form. If made from carbon nanotubes (recently fabricated into sheet form) or graphene (a sheet-like carbon allotrope), the major structural materials can be produced using carbon dioxide gathered in situ from the atmosphere. The recently synthesised amorphous carbonia might prove a useful structural material if it can be quenched to STP conditions, perhaps in a mixture with regular silica glass. According to

Birch's analysis such colonies and materials would provide an immediate economic return from colonizing Venus, funding further terraforming efforts.

In remarking that the ground is too far below the one-atmosphere level, Landis echoes the descriptions of the planets Rustom, in the novel *Orbit Unlimited* by Poul Anderson, and Plateau, in *A Gift from Earth* by Larry Niven. Each has a dense poisonous atmosphere, with a small region of land rising to a habitable level.

## Terraforming



Artist's conception of a terraformed Venus.

Terraforming (literally, "Earth-shaping") is the theoretical process of modifying a planet, moon, or other body to a more habitable atmosphere, temperature, or ecology. Venus has been the subject of a number of terraforming proposals. The proposals seek to remove or

convert the dense carbon dioxide atmosphere, reduce Venus's 500 °C (770 K) surface temperature, and establish a day/night light cycle closer to that of Earth's.

Most proposals involve deployment of a solar shade and/or a system of orbital mirrors, for the purpose of reducing insolation and providing light to the dark side of Venus. Another common thread in most proposals involves some introduction of large quantities of hydrogen or water. Proposals also involve either freezing most of Venus's atmospheric CO<sub>2</sub>, or converting it to carbonates, urea or other forms.

### **Colonies in Venus Orbit**

Another promising pathway to colonization is the use of near-Venus space for the orbital capture and development of comets and asteroids. Although Venus currently has no moons, in the near future it may be practical to nudge smaller bodies into orbit around the inner planets. Venus is especially good for this because aerobraking in its thick atmosphere can be used to slow these bodies down. Unlike near-Earth space where the danger of hitting the Earth would have severe effects on the civilization, near-Venus space does not suffer from this problem. The available free solar energy from the Sun makes Venus a desirable location for industrial development.

It is also a likely precursor to any serious attempt to develop economic activity in the gravity well of Venus. Resources in Venus orbit would be used to extend activity downward. A space elevator would likely not be feasible, given Venus' slow rotation (243 Earth days), but a skyhook into the atmosphere is possible.